State of California
Department of Transportation
New Technology and Research

TRAFFIC NOISE ATTENUATION AS A FUNCTION OF GROUND AND VEGETATION

(FINAL REPORT)

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TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
FHWA/CA/TL-95/23		

4. TITLE AND SUBTITLE TRAFFIC NOISE ATTENUATION AS A FUNCTION OF GROUND AND VEGETATION (FINAL REPORT)	5. REPORT DATE June 1995 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Rudolf W. Hendriks	8. PERFORMING ORGANIZATION REPORT NO. 65328-637327
9. PERFORMING ORGANIZATION NAME AND ADDRESS California Department of Transportation Engineering Service Center Office of Materials Engineering and Testing Services Testing and Technology Services Branch 5900 Folsom Boulevard Sacramento, California 95819	10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. E85TL18
12. SPONSORING AGENCY NAME AND ADDRESS California Department of Transportation Sacramento, California 95807	13. TYPE OF REPORT & PERIOD COVERED Final 1985-95 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was performed in cooperation with the U.S. Department of Transportation, Federal Highway Administration, under the research project titled "Traffic Noise Attenuation as a Function of Ground and Vegetation".

16. ABSTRACT

This final report presents the results of measured excess attenuation rates for traffic noise propagating over acoustically absorptive terrain in terms of the α site parameter, as used in the FHWA Highway Traffic Noise Prediction Model (FHWA-RD-77-108). The study was part of a federally-funded research project that focussed on two noise propagation phenomena: 1) excess attenuation provided by various ground covers; 2) shielding by shrubs and trees typically used in landscaping along freeways. Results of the latter were published in a 1989 interim report (FHWA/CA/TL-89/09) by the same title and author. A summary is repeated in this report.

Noise levels of single vehicle passbys were measured at distances from 7.5 to 122 m (25 to 400 ft), and at heights from 0.8 to 6 m (2.5 to 20 ft) above the ground. A total of 541 measurements were made using up to ten microphones simultaneously at four acoustically absorptive ("soft") sites. Additional verification measurements were made at four-lane highway sites. Meteorological parameters were measured simultaneously with the noise. Excess attenuation rates in terms of α were calculated from the data.

Final analysis revealed that α is distance, as well as height, dependent. Due to its height dependency, α also proved to be vehicle (source) dependent for a given receiver height and distance. For the purpose of noise propagation, α can be segregated by two vehicle source groups: 1) heavy trucks, and 2) autos and medium trucks (definitions per FHWA-RD-77-108). α vs. distance (D) relationship can be described by hyperbolic equations of the form $\alpha = a - b/D$; α vs. average noise path heights (H) can be expressed as linear equations: $\alpha = a - bH$, where a and b are constants in both cases. The α scheme as presently used in the FHWA Model causes average over predictions of 2 dBA between 30 and 61 m (100 and 200 ft), and 4 dBA between 61 and 122 m (200 and 400 ft). It is recommended that the α scheme be discontinued in future models in favor of better propagation algorithms.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Highway traffic noise prediction, noise propagation, noise attenuation rates, excess attenuation, noise and vegetation, vehicle noise	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS - TL - 1242 (Rev. 6/76)

NOTICE

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2) square feet (ft^2) acres	6.432×10^{-4} .09290 .4047	square metres (m^2) square metres (m^2) hectares (ha)
Volume	gallons (gal) cubic feet (ft^3) cubic yards (yd^3)	3.785 .02832 .7646	litre (l) cubic metres (m^3) cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s	28.317	litres per second l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G) (ft/s^2)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) (1000 lbs) kips	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (in-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch ($ksi\sqrt{in}$)	1.0988	mega pascals$\sqrt{metre}$ (MPa $\overline{m}$)
	pounds per square inch square root inch ($psi\sqrt{in}$)	1.0988	kilo pascals$\sqrt{metre}$ (KPa $\overline{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{+F - 32}{1.8} = +C$	degrees celsius (°C)
Concentration	parts per million (ppm)	1	milligrams per kilogram (mg/kg)

ACKNOWLEDGEMENTS

A research project of this magnitude obviously has to have the cooperation of many people. Team work is of the essence, and the Principal Investigator of this project was very fortunate to have the expert assistance from the following personnel:

- **Gene Lombardi**, who maintained and calibrated the sound level meters, made special cables and connectors, and helped with the complicated instrument setups and field measurements; his contribution as a trouble shooter was invaluable

- **Bob Cramer**, who helped with the instrument setups and field measurements; his expertise in meteorological instrumentation was essential to the success of this project

- **Bob Dawson** (on temporary assignment), who created various specialized computer programs for data analysis; his innovative approaches simplified and streamlined the analysis process

- **Dick Wood**, who provided computer support and valuable advice on the project; in spite of a heavy work load, he always managed to quickly respond and assist the Principal Investigator

- **Dave Brent** (on temporary assignment), who helped with the field work; in his short time with us, he quickly learned to perform the specialized tasks required in this project

- **Irma Gamarra-Remmen** and **Ken Wahl**, who provided the quality illustrations in this report, often at short notice, always with professionalism

The Principal Investigator wishes to thank the above personnel for their excellent work and dedication. Without their support this research project could not have been completed.

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INTRODUCTION

This is the final report of a Federal Highway Administration (FHWA) - funded research project titled: "Traffic Noise Attenuation as a Function of Ground and Vegetation." An interim report by the same title and author was published in September, 1989 (1), and will from here on in be simply referred to as the "interim report".

The research was performed by the California Department of Transportation (Caltrans), Division of New Technology and Research (DNTMR), formerly called the Office of Transportation Laboratory (TransLab), and later (until the most recent name change to DNTMR), the Office of Transportation Materials & Research. The project focussed on two separate site specific phenomena relating to traffic noise attenuation:

1. Excess attenuation caused by various ground covers as functions of distances up to 122 m (400 ft) from traffic sources and of heights up to 6 m (20 ft) above the ground.

2. Shielding by shrubbery and trees of various thicknesses and density typically used in landscaping along highways (vegetative barriers).

Work on the second phenomenon (vegetative barriers) was completed first, and the final findings and conclusions were presented in the interim report.

Work on the first phenomenon (excess attenuation) was still in progress when the interim report was written. However, most of the field work and some of the data analysis had been performed, and the interim report included some preliminary findings concerning the ground attenuation rates, as well as detailed information on background, sites and methodology.

Although all findings and conclusions (including those of the interim report) were summarized in this report, the author intended to use the latter as a continuation of the interim report. It was inevitable that a certain amount of repetition appeared. However, the author attempted to keep overlap between the two reports to a minimum.

In this report, coverage of the vegetative barrier section (already finalized in the interim report) was limited to the conclusions only. Almost all of the information in this final report therefore pertains to coverage of the excess attenuation portion of this research project.

Since this report frequently refers to pertinent information discussed in detail only in the interim report, the author advises readers interested in the details of this research, to read, or have ready access to, a copy of the interim report.

Background

The need for this research project was thoroughly discussed in the "Background" chapter of the interim report. Earlier Caltrans research (2) produced evidence that the FHWA Highway Traffic Noise Prediction Model (3) (FHWA Model) does not adequately account for ground absorption, or excess attenuation. The site parameter α appears to be too restrictive with its two choices of:

* 0 for an acoustically hard site (reflective)
* 0.5 for an acoustically soft site (absorptive)

Data from the earlier research also indicated that situations where $\alpha > 0.5$ are quite common, and that perhaps higher values should be used for the majority of absorptive sites.

The reason for the vegetative barrier portion of this study stemmed from casual, unreported observations during the earlier Caltrans research project (2) and subsequent measurements. These uncontrolled measurements held some promise that relatively thin strips of vegetation of at least 4.5 m (15 ft) wide and 2.5 m (8 ft) high could provide several dBA attenuation. If true, strategically placed freeway landscaping could be used for traffic noise mitigation measures in lieu of expensive conventional noise barriers.

Objectives

The objectives of this research project as outlined in the original proposal were:

1. Measure traffic noise attenuation rates as a function of distance from source, height above ground, and absorptive characteristics of six ground types, ranging from reflective paved surfaces to soft, plowed dirt and ground covers.
2. Measure traffic noise attenuations provided by four species and three heights or thicknesses of vegetation belts alongside highways, such as ivy covered fences, dense oleander and other shrubbery.
3. Establish improved traffic noise attenuation rates and shielding values to be used as inputs for Caltrans noise prediction methods, based on findings in this study.
4. Develop guidelines for use of evergreen vegetative belts (barriers) in Caltrans noise abatement procedures, if effectiveness were proven in this study.

Although the original objectives of this project have not changed in principle, they have changed in scope. The difficulty in finding suitable sites, logistical and environmental problems were responsible for these changes. Most of the problems were discussed in detail in the interim report.

Findings of the Interim Report

The interim report discussed the final results of the vegetative barrier portion of the research project, and some preliminary results of ground attenuation rates. Following is a short summary of the findings.

Vegetative Barriers

After detailed measurements and analyses at three sites, the principal investigator concluded that vegetative barriers are not an effective highway noise mitigation measure to be used on a routine basis. The site information, measuring procedures, measurement data, analysis results, and conclusions were all finalized in the interim report. The supporting information concerning vegetative barriers is not covered in this report. However, a recap of the final findings is shown in the conclusions of this report.

Excess Attenuation and Ground Attenuation Rates

Preliminary findings showed that the 0.5 soft site α used in the FHWA Model appears to be too low for the sites measured. The preliminary results were based on noise data at four soft sites, gathered at microphones 1.5 m (5 ft) above the ground and 15 and 61 m (50 and 200 ft) from single line sources. The α values averaged well in excess of 1.0 at these distances.

RESEARCH APPROACH

The research approach discussed in this section will pertain to the excess attenuation portion of this project only. The vegetative barrier research approach was covered in detail in the interim report.

The research approach for determining α values for various types of terrain changed several times from the original proposal. The changes as well as various reasons responsible for the changes are discussed in the following sections.

Site Selection

The original proposal envisioned measuring α values of six different homogeneous ground covers ranging from reflective (such as paved surfaces) to extremely absorptive (such as a field with tall weeds or shrubbery). The exact ground cover specifications would be determined in the reconnaissance and site selection stage of the project. The work plan called for selecting three sites in each ground cover category, or eighteen sites total. During site reconnaissance throughout California, it became evident that the selection of suitable sites was very limited, and that the total number selected would fall far short of the eighteen sites proposed.

The ideal site for studying attenuation rates consists of flat, open, and homogeneous terrain surrounding a single, heavily traveled traffic lane. Such a site would have all the desirable qualifications to measure the noise attenuation with distance and height: a continuous high-level noise source, approximating a line source with a well defined location, a uniform ground surface, no obstructions or reflective surfaces, space to set up an array of microphones at various heights and distances, and a low background noise.

The "real world" situation closest to the ideal site would be that of a two-lane highway in an isolated rural area. Such a highway, however, would not be expected to have the substantial traffic volumes necessary for a high and continuous noise source level. In fact, rural traffic is most often characterized by low volumes with large gaps between vehicles. The corresponding noise levels fluctuate from near background levels to occasional high peaks when vehicles pass by. Noise levels, energy-averaged over time, would be low.

An obvious remedy for the low noise source levels would be to select a major, multilane rural highway. However, the trade-off for the higher noise levels would be the loss of the single line source location. A multilane highway consists of at least several line sources occurring simultaneously at different, but known, source-to-receiver distances. Relative source contributions to the total noise level measured at a given location, however, cannot be isolated by measurement alone. These individual contributions can of course be calculated from measured traffic volumes, mixes and speeds. Even then, no single, fixed centroid can be assumed from which the noise propagates outward at a uniform rate.

The approach used in this study was to first select rural two-lane highways for determining the α values from well-defined source locations using single vehicle passbys. Later, multi-lane highway sites were selected, for comparison of measured vs. FHWA Model predicted hourly noise levels, using the α values derived from single events. Because of the obvious increase in scope and complexity of the project due to measurements of single vehicles as well as multi- lane traffic "streams", the amount of sites selected had to be limited. A total of six sites were chosen: four for single event and two for multi-lane traffic stream measurements. However, one of the single event sites, a two-lane highway, was also used for traffic stream measurements, effectively making the total seven sites, of which three were traffic stream sites.

Single Vehicle Passby Method

In order to maintain the single source aspect of an ideal site, the approach used in this project was to first study single vehicle passes on very low volume two lane highways. If the noise from a passing vehicle is measured over a time interval, the moving vehicle (point source) behaves as a line source (3). A trace of the instantaneous noise levels from the vehicle would, at some point in time, begin to register above the ambient noise as it approaches, increase to a maximum value, and decrease again to a point in time when it dips below the background noise. The energy averaged noise (L_{eq}) measured over the time period defined by the time that the vehicle noise is above the background noise would be considerably higher than the L_{eq} measured over a longer time including gaps in traffic. Appendix A, pages A-2 and A-3 show the relationship of the hourly L_{eq} of a typical heavy truck passby and the L_{eq} for the duration of passby. As long as the background noise is at least 10 dBA lower than the L_{eq} of the vehicle passby, the latter is not contaminated.

If energy averaged noise measurements are made at two distances from the source simultaneously, the α value can be calculated from the difference in the two measured L_{eq}'s (ΔdBA). This procedure is shown in Appendix B of the interim report. The calculation method is repeated in this report in Appendix A, Pages A-4 through A-7. The two L_{eq}'s measured at two different distances simultaneously from a vehicle passby, must be normalized first to an "infinite" segment for calculation of α as used in the FHWA Model.

Pages A-4 and A-5 show the procedure used to normalize the differences in measured single vehicle passby L_{eq}'s (dBA) from finite to infinite roadway segments, using a reverse segment adjustment process. FHWA Model algorithms were used for this method. The normalizations were necessary to deal with the unequal segments caused by measurements taken at two different distances. The example shows two receivers only. In this study, as many as ten microphones measured noise levels simultaneously at different distances and heights. However, during the analyses the data were paired to calculate the ΔdBA values.

After normalizating the ΔdBA's, the α values can be calculated using the equations shown on pages A-6 and A-7. Two equations are shown, one for L_{eq} measurements, and one for L_{max} values. The L_{max} descriptor is the "instantaneous" highest noise level measured at both receivers shown.

According to the FHWA Model methodology, α values derived from the L_{max} data equal those derived from the L_{eq} data (3). The underlying assumption, however, is that the site is perfectly homogeneous. In this study, both L_{eq}'s and L_{max}'s were measured during all single event passby's, and both were used to calculate α values.

The α calculations will be discussed in greater detail in the Data Analyses chapter of this report.

Multi-Lane Traffic Stream Verification

This portion of the ground attenuation study incorporated a number of 30-minute L_{eq} measurements at three sites. These measurements were made simultaneously at various distances up to 122 m (400 ft) from the centerline of the nearest lane, at a height of 1.5 m (5 ft). Traffic was counted simultaneously, and later input in the FHWA Model, along with α values derived from the single event data, for verification. Data from a fourth site used in a previous research project (4) was also used for the α verifications.

MEASUREMENT SITES AND INSTRUMENTATION

Single Event Sites and Instrument Setup

Four single event sites were selected, and labeled G-1 through G-4 Each site is in flat, open terrain surrounding a two-lane rural highway with very low traffic volumes. Three of the four sites are located in California's Central Valley, and one in a desert region east of the Sierra Nevada Mountains at the north end of Owens Valley.

Figure 1 shows the general requirements developed for all sites in this study. Terrain needed to be level with the roadway, homogeneous in ground cover and soil, and clear of any obstructions or reflecting surfaces within the limits shown.

The microphone (mic) locations for the single event instrumentation setups are shown in Figure 2. Since ten mic's were used simultaneously, the eighteen mic locations shown were divided in two setups, as shown in Figure 2. The 1.5 m (5-ft) high mic at 15 m (50 ft) was used in both setups.

The following sound level meters (SLM) and other equipment were used for the noise measurements:

* Six Bruel & Kjaer (B & K) 2218 Precision SLM with B&K 4165 mic's.
* Three B&K 4426 Noise Analyzers with B&K 4165 mic's.
* One B&K 2230 SLM with B&K 4155 mic.
* One datalogger, custom-built for the Division of New Technology, Materials and Research.
* One B&K 4320 Calibrator (one master calibrator was used to calibrate all equipment in the field).
* One Belfort Instruments "hand held" Anemometer, mounted on a standard at a height of 2.1 m (7 ft).

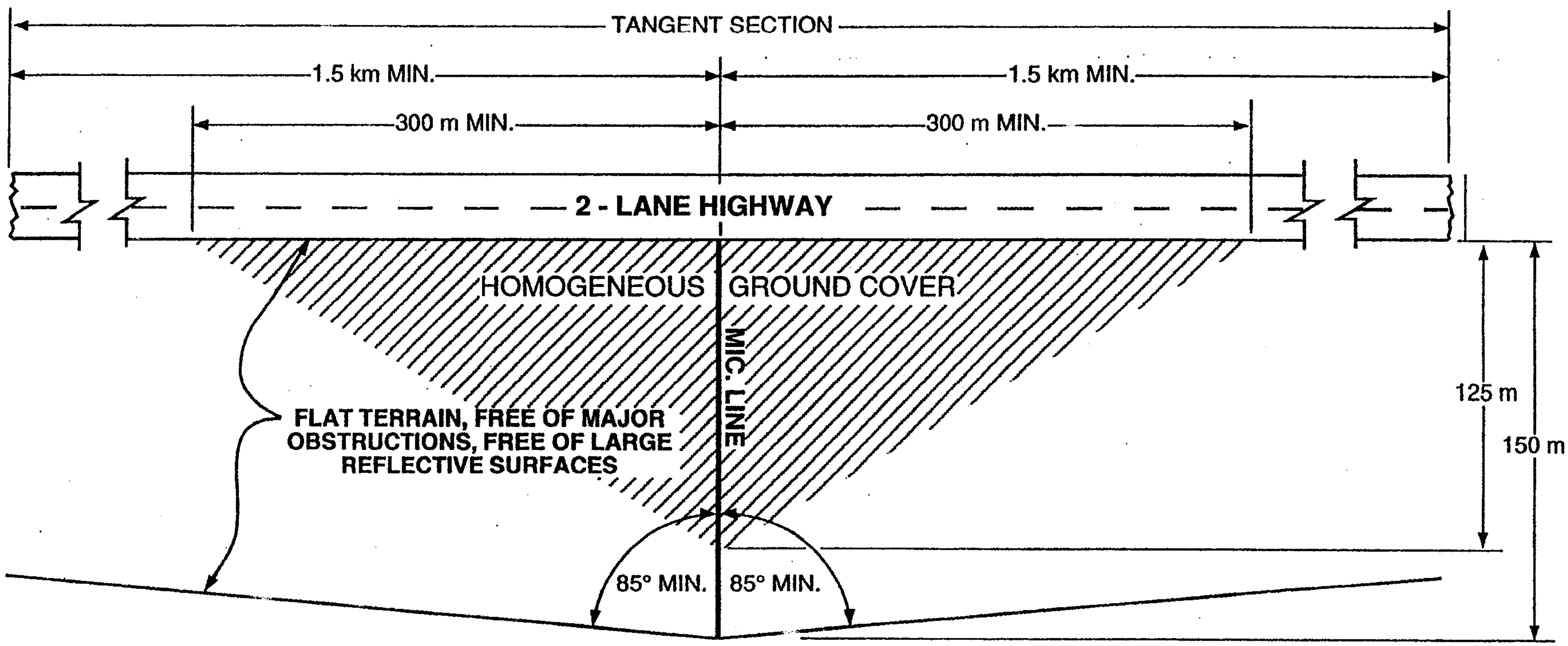


Fig. 1. GENERAL SITE CRITERIA

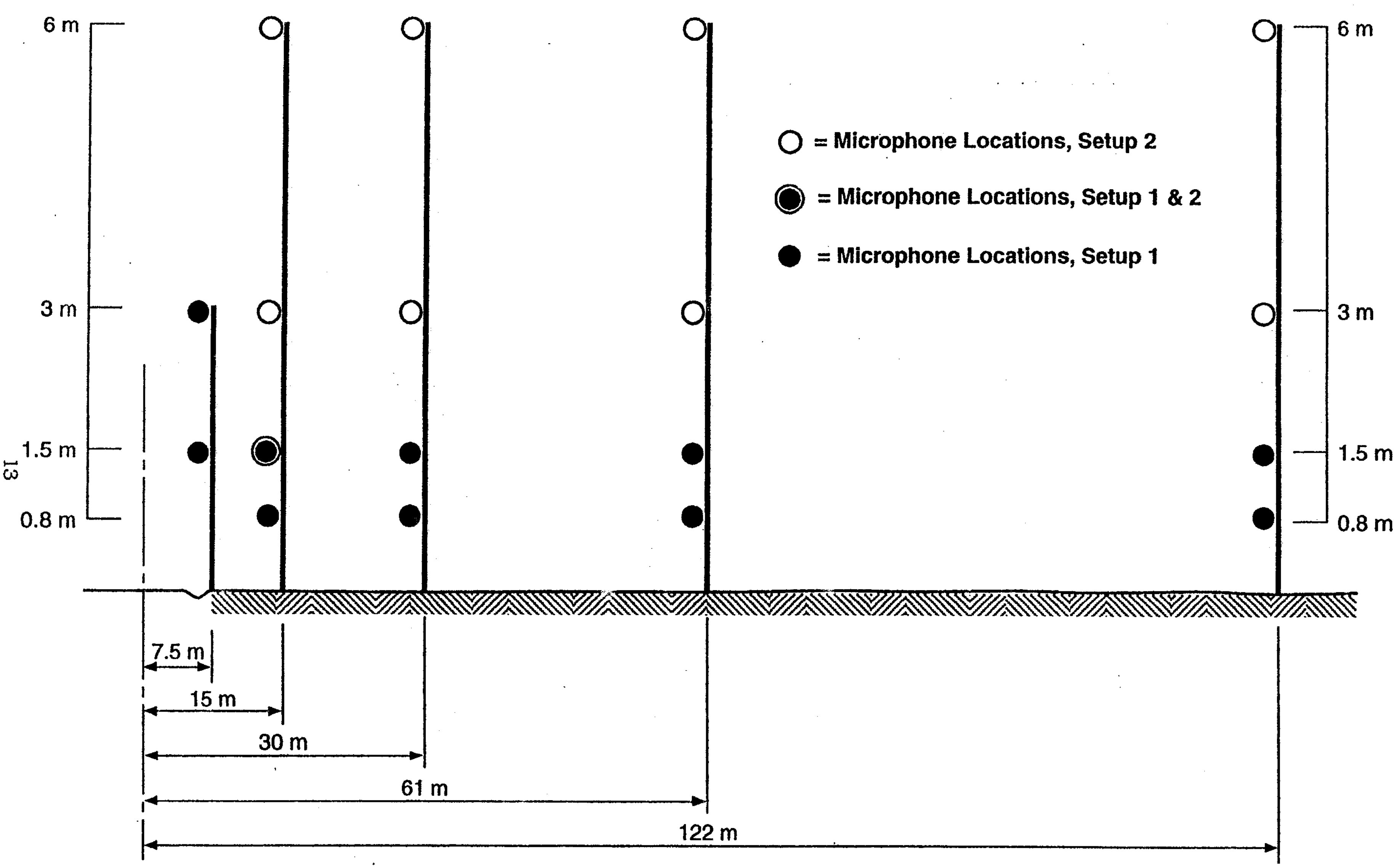


Fig. 2. MICROPHONE LOCATIONS, SINGLE EVENTS

* One Decatur Electronics Inc. Range Master 715 Radar Gun.

All SLM's were field calibrated as a system with the datalogger. In addition to the field calibration, all the equipment was calibrated in the Division of New Technology, Materials and Research (NTM&R) laboratory prior to the research project. The NTM&R has a Quality Assurance Program which is traceable to the National Institute of Standards and Technology (NIST) (formerly National Bureau of Standards) in Washington, D.C., via two B&K 4160 Laboratory Standard Microphones which are calibrated annually by NIST.

Figures 3 through 6 show the area maps of sites G-1 through G-4. Following is a listing of the sites with brief descriptions of their locations and site characteristics:

* **G-1 "Kesterson"** is along eastbound State Route (SR)-140, 6.4 km (4.0 mi) northeast of Gustine and the junction of SR-33 and SR-140, at the Kesterson Wildlife Refuge, in the Central Valley. <u>Ground cover</u>: 0.3 to 0.6 m (1 to 2 ft) tall dense weeds and grasses, with silty soil (Figure 3).

* **G-2 "Bishop"** is located east of the Sierra Nevada Mountains, at the north end of the Owens Valley, about 11.4 km (7.0 mi) north of Bishop, along northbound Route US-6. <u>Ground cover</u>: 0.6 to 0.9 m (2 to 3 ft) tall sage bushes, average diameter 3 feet (0.9 m), average separation about 1.5 m (5 ft), with sandy soil (Figure 4).

* **G-3 "Lemoore"** is along westbound SR-198, 17.7 km (11.0 miles) east of Interstate Highway (I)-5, in the Central Valley. <u>Ground cover</u>: none, plowed field with 150 to 200 mm (6 to 8 in) deep furrows, clay soil (Figure 5).

* **G-4 "Avenue 7"** is along eastbound Avenue 7, 21 km (13 mi) east of Firebaugh, and approximately 24 km (15 mi) southwest of Madera, in the Central Valley. <u>Ground cover</u>: 75 to 300 mm (3 to 12 in) high weeds, sparse, with silty soil (Figure 6).

All sites are considered "soft" sites according to the definition of FHWA-RD-77-108(<u>3</u>). Site cross sections of the above sites are shown in Appendix B of this report.

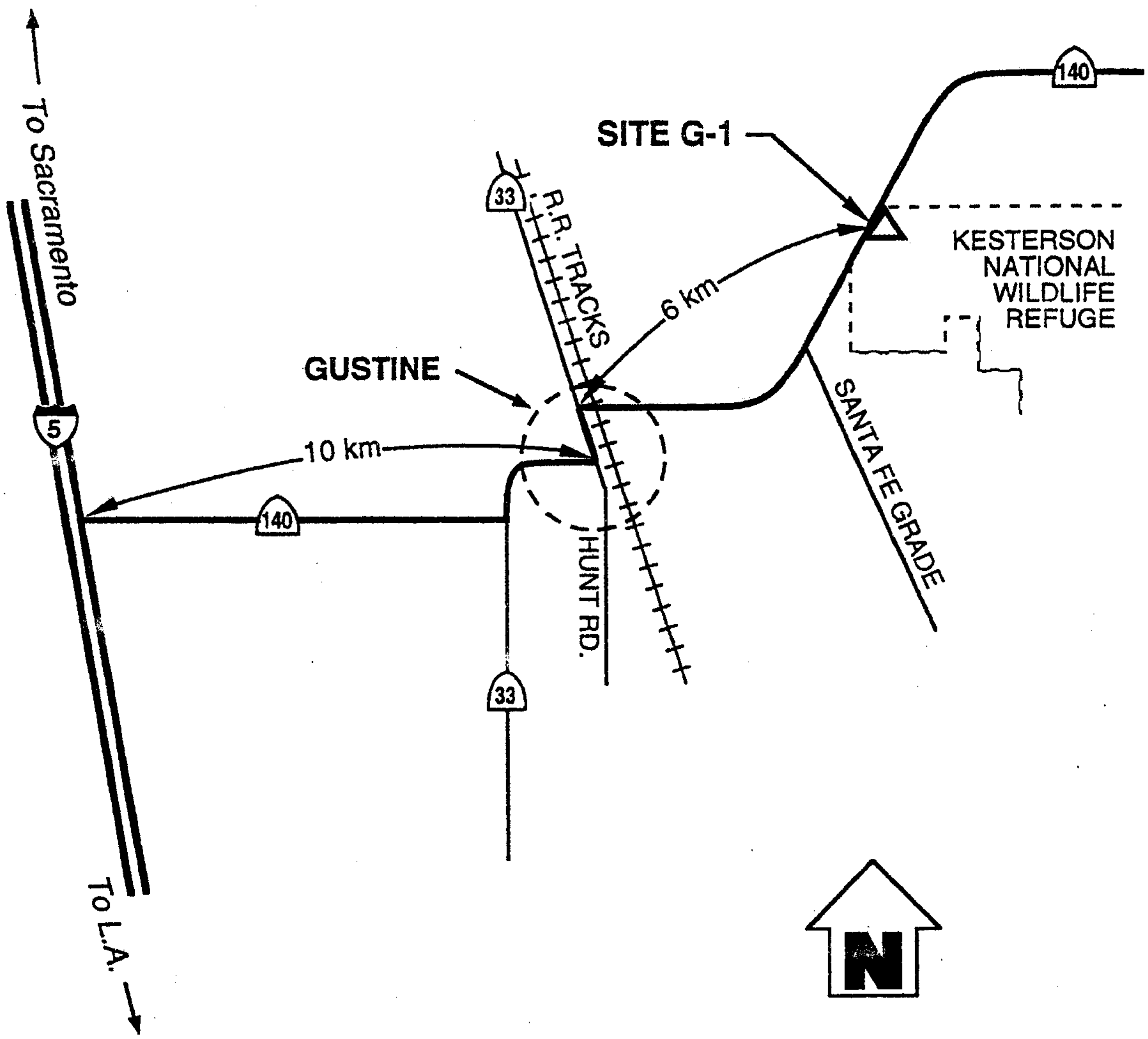


Fig. 3. AREA MAP OF SITE G-1 "KESTERSON"

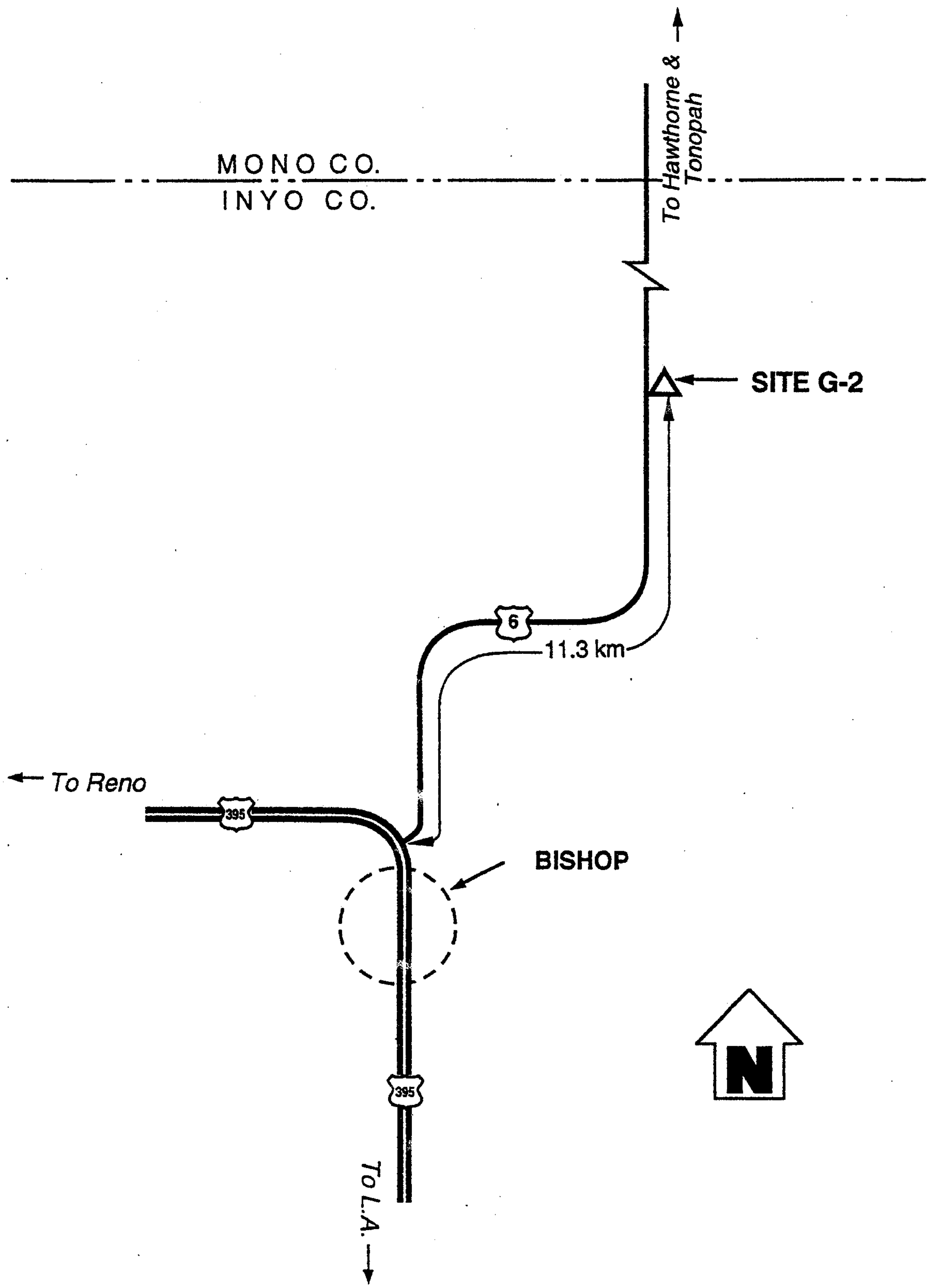


Fig. 4. AREA MAP OF SITE G-2 "BISHOP"

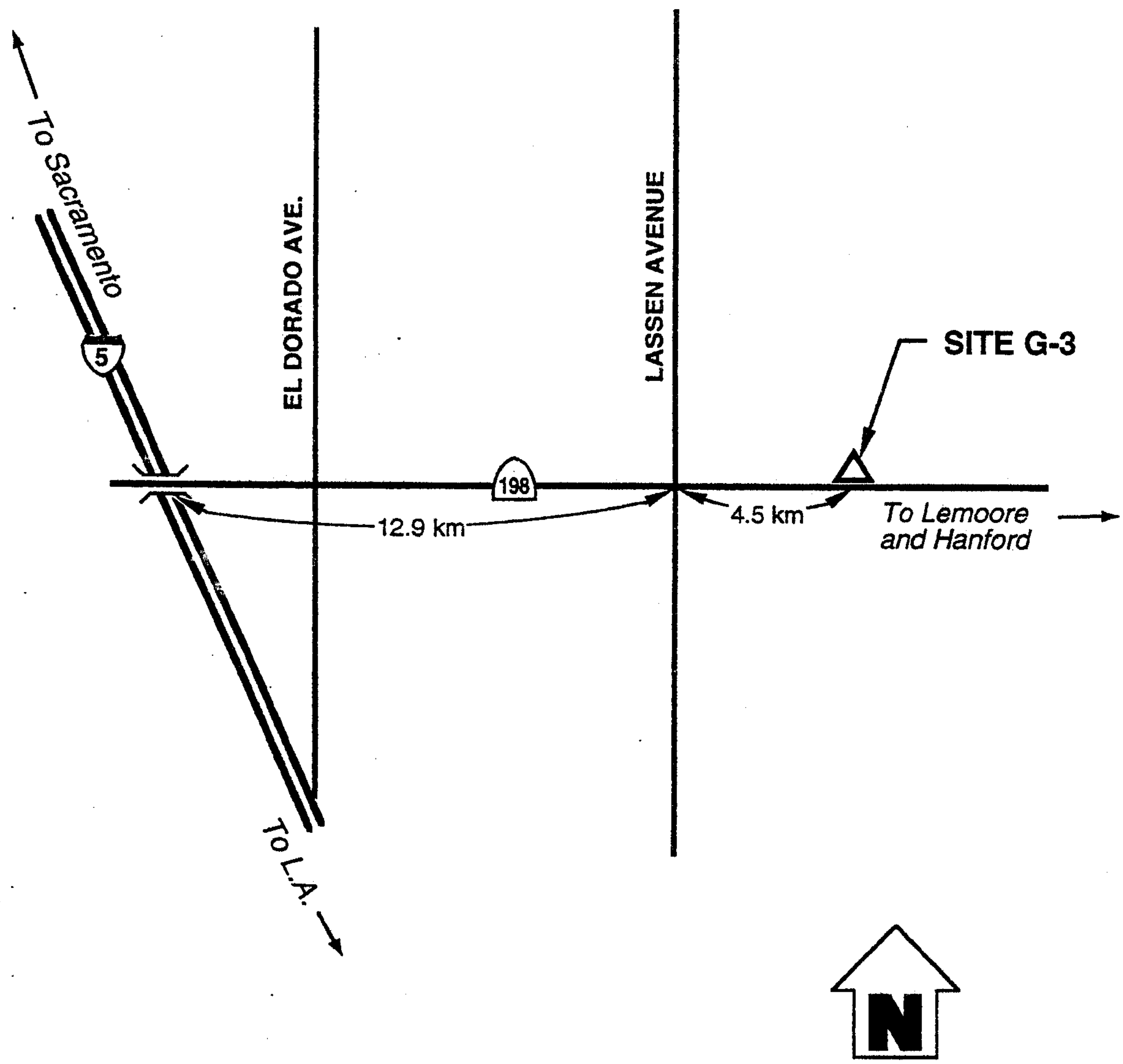


Fig. 5. AREA MAP OF SITE G-3 "LEMOORE"

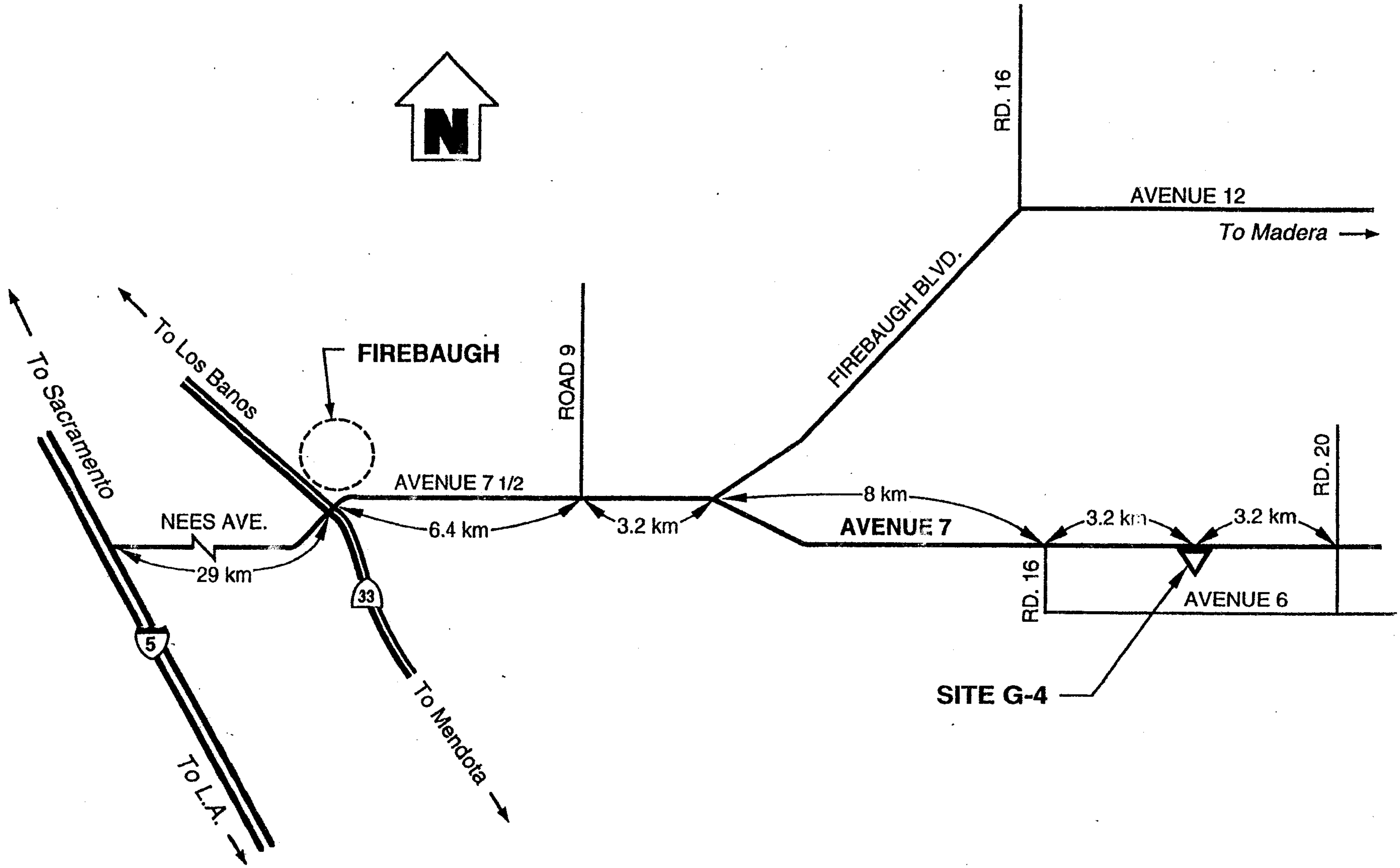


Fig. 6. AREA MAP OF SITE G-4 "AVENUE 7"

Multi-Lane Verification Sites

The criteria for multi-lane verification sites were the same as those for the single events sites. Site G-1 doubled as a multi (two)-lane verification site. In addition to G-1, two more sites (G-7A and G-8) were selected in California's Central Valley for multi-lane α verifications. Both sites are located along I-5, a major four-lane interstate highway. Two lanes each direction were separated by a 25.6 m (84 ft) wide dirt median. This directional separation of lane groups placed the line sources at two widely different distances from each receiver, representing extreme conditions, and a good test for newly derived α values.

Figure 7 shows the generalized instrument setup for the verification sites. Due to time limitations, only 1.5 m (5 ft) high mic's were used for the α verifications. Five mic's were placed at 7.5, 15, 30, 61, 122 m (25, 50, 100, 200, and 400 ft) from the centerline (CL) of the near lane at site G-1, and from the CL of the near lane groups (dividing line between the two near lanes) at sites G-7A and G-8.

Figure 8 shows the area maps of sites G-7A and G-8. Following is a listing of the two sites with brief descriptions of their locations and site characteristics:

* **Site G-7A** is located along Interstate I-5, 2.4 km (1.5 mi) north of the Kern/Kings County line, on the west (Southbound) side of the freeway, in the Central Valley. <u>Ground cover</u>:0.6 to 0.9 m (2-3 ft) tall bushes, about 1 m (3.3 ft) average in diameter, spaced about 1.5 - 3 m (5-10 ft), with silty soil.

* **Site G-8** is located along I-5, 18.1 km (11.3 mi) (north of the Kern/Kings County line, and 1.6 km (1 mi) south of Utica Road, on the east (Northbound) side of the freeway. <u>Ground cover</u>: about the same as site G-7A.

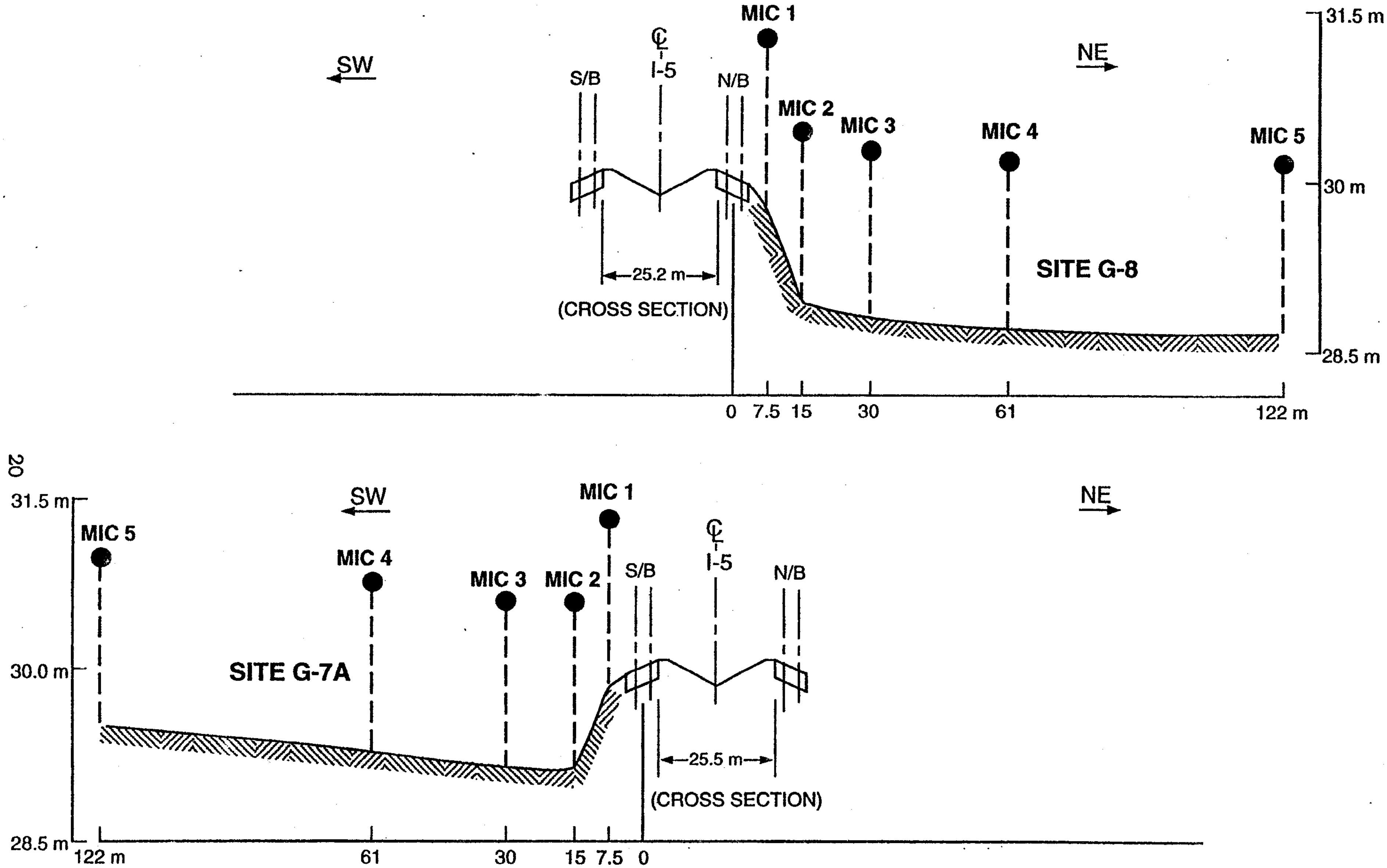


Fig. 7. VERIFICATION SITES, MIC LOCATIONS

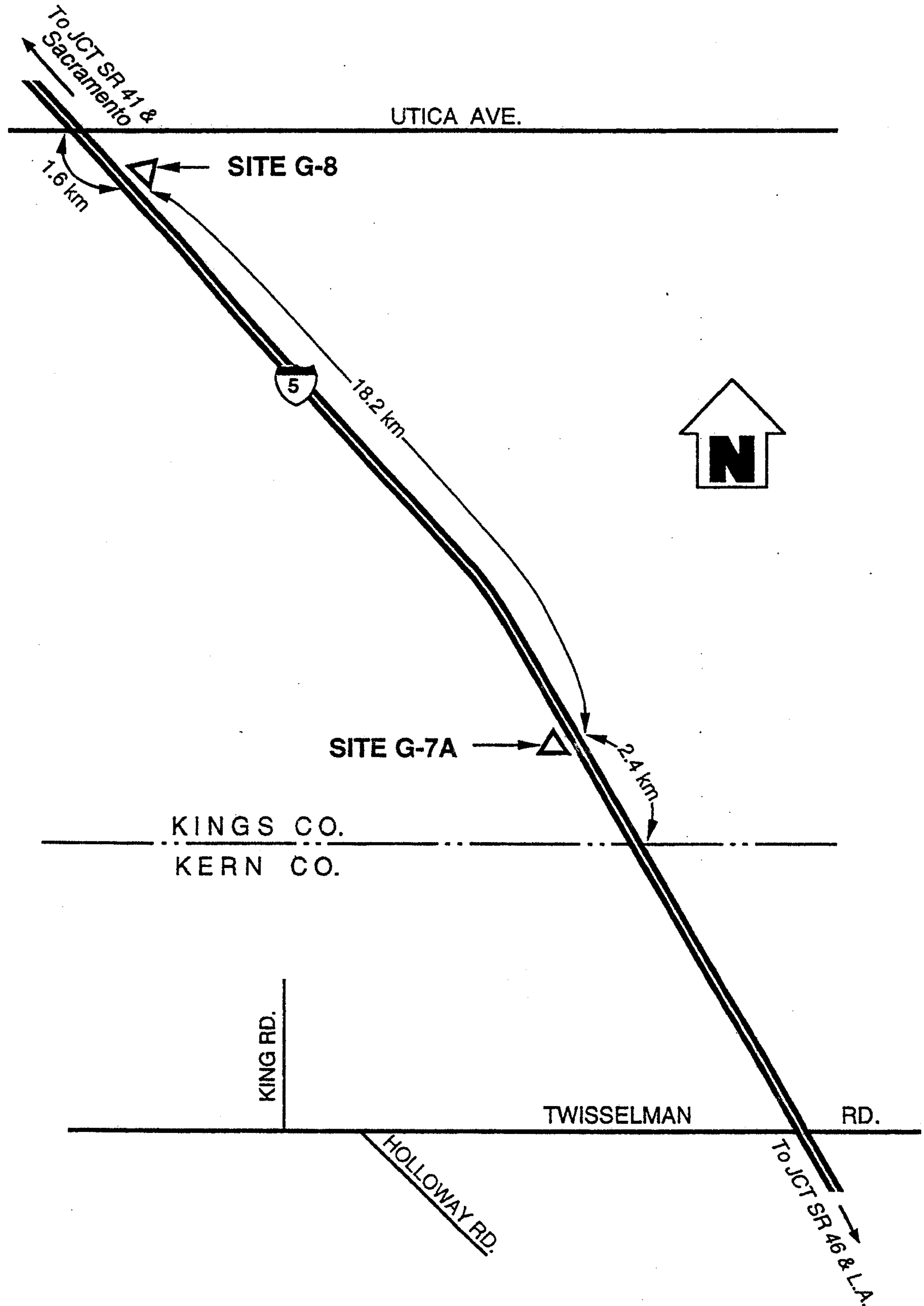


Fig. 8. AREA MAP OF SITES G-7A AND G-8 (VERIFICATION SITES)

Data from a site (PB99) used in a previous research project (4) were also used for α verification in this report. Cross sections of all verification sites (including PB99) are shown in Appendix B of this report.

MEASUREMENTS

Measurement Procedures and Data Recording

A team of two persons surveyed the site, set up and calibrated all instrumentation. During the measurements the team observed and recorded vehicle passby information, meteorology, ambient noise, and switched instruments on and off for each vehicle passby.

One of the observers switched on the datalogger from the time the vehicle noise level - measured at the 1.5 m (5 ft) high mic at 122 m (400 ft) from the source - rose over the low and fairly constant ambient noise, and turned it off when the vehicle noise dipped below ambient levels. The noise data (L_{eq} and L_{max}) at the ten mic's were simultaneously recorded by the datalogger. The same observer also recorded wind speed and direction at a height of 2.1 m (7 ft), temperature, relative humidity, sky conditions, and ambient noise levels (before and after each passby) for each vehicle pass. A typical vehicle pass lasted from 30 to more than 60 seconds, depending on the vehicle's speed and the ambient noise level at the beginning and end of the measurement run. During this time period the wind usually fluctuated in both speed and direction. The observer "eyeball-averaged" these fluctuations.

The other observer recorded the elapsed times from the beginning of passby to the point of passby, the total elapsed time of the passby, and vehicle types according to the FHWA RD-77-108 definitions of autos, medium trucks, and heavy trucks (3). The same observer also measured (by radar) and recorded vehicle speeds. The elapsed time and speed information was later used to calculate the finite roadway segments discussed previously.

The purpose of recording the ambient noise level was to ascertain that the L_{eq} measurement at each receiver was not contaminated by background noise or the noise "floor". If the ambient noise level was less than 10 dBA below the L_{eq} measurement, the latter was be considered contaminated, and was not included in the data analysis.

Due to a lack of state-of-the-art datalogging and recording systems (e.g. interfacing with laptop computers) the various types of data were either hand-recorded by the operators/observers or "dumped" on paper strip charts by a datalogger, depending on the type of data collected. Specifically, the data collected at each site included:

* Site survey data (forms A-1, A-2, A-3):
    - Station line and site alignment notes (form A-1)
    - Station line profile data (form A-2)
    - Cross section data (form A-3)
* Instrumentation (form B):
    - Event No.'s
    - Mic positions (numbers, distances and heights)
    - Instruments (brands, models, and serial No.'s)
* Vehicle observations (form C):
    - Event No.
    - Vehicle speed
    - Vehicle type (Auto, Med. Truck, Heavy Truck)
    - Duration from begin passby to point closest to observer
    - Total time of passby
* Environmental observations (Form D):
    - Event No.
    - Ambient noise immediately before and after the passby
    - Sky condition
    - Average wind speed and direction during event
    - Relative humidity
    - Air temperature
* Datalogger (printed out on strip chart):
    - Event No.
    - Passby L_{eq}
    - Passby L_{max}

- Statistical information such as L_{10}, L_{50}, standard deviation, skewness and kurtosis.

Appendix B shows examples of the various forms on which the data were recorded, as well as sample input files for computer analysis.

For the multi-lane verification measurements, the entire traffic stream was measured for 30 minutes. During this time directional traffic was counted, traffic speeds were measured by radar, and meteorological observations were made.

Number of Measurement Runs

For the purposes of this report a measurement run is defined as the entire set of simultaneous noise measurements at all mic locations, as well as meteorological measurements, vehicle identifications or traffic counts, and associated vehicle/traffic speeds. For single event sites one individual vehicle passby was included in each measurement run. For multi-lane verification measurements, each measurement run lasted 30 minutes. This averaging time proved to be adequate to "stabilize" the L_{eq} display on the SLM's, considering the low traffic volume characteristics of the verification sites.

The following number of measurement runs were made at each site, followed by a breakdown by vehicle type as defined in FHWA-RD-77-108 (3) report:

Single Event Sites (Individual Vehicle Passbys):

* Site G-1: 159 Measurement Runs (77 Autos, 8 Medium Trucks, 74 Heavy Trucks)

* Site G-2: 298 Measurement Runs (242 Autos, 5 Medium Trucks, 51 Heavy Trucks)

* Site G-3: 56 Measurement Runs (22 Autos, 5 Medium Trucks, 29 Heavy Trucks)

* Site G-4: 28 Measurement Runs (19 Autos, 3 Medium Trucks, 6 Heavy Trucks)

* Total: 541 Measurement Runs (360 Autos, 21 Medium Trucks, 160 Heavy Trucks.

Multi-Lane Verification Sites (30-Minute Runs):

* Site G-1: 12 Measurement Runs

* Site G-7A: 16 Measurement Runs

* Site G-8: 7 Measurement Runs

* Total: 35 Measurement Runs

In addition to the above, measurements at a site named PB99 from an earlier research project (4) were also used for multi-lane verification. The data included six 15-minute runs without a noise barrier and sixteen runs with a 4.3 m (14 ft) high noise barrier, effective height 3 m (10 ft) above the pavement. Each run included eleven mic locations, two reference mic's near the highway and nine mic's at distances ranging from 18 to 74 m (58 to 243 ft) from the nearest lane group, at heights from 1.5 to 7 m (5 to 23 ft) above the ground.

Measurement Results

Due to the large amount of simultaneous single event data measured, only examples of the results are shown in this report (see Appendix B). However, all the data are on file at the Caltrans Office of Environmental Engineering in Sacramento.

DATA ANALYSES

Data Preparation

The various data for each event were later entered into the following five separate computer data base files for each site:

1. Passby L_{eq} data at all mic's
2. Passby L_{max} data at all mic's
3. Mic position data (mic #, distance, and height)
4. Vehicle passby data (vehicle type, speed, duration of first half of passby, and total passby time)
5. Environmental data (ambient noise, wind speed, wind direction, relative humidity, temperature, and sky condition)

The matching data sets for each event were linked by way of a unique identification (ID) number consisting of the site number and event number (e.g. G2-43 denotes site G2, event No. 43). The ID No. was located in the first column of each file. A special program was later written to access data from each file necessary for the analyses.

α Calculations

The first step in analyzing the data was to calculate the α parameters from paired noise data for all single event passbys. The noise level differences between any two mic locations can be expressed in terms of α from the following relationships valid for infinitely long line sources and stationary point sources, respectively (3):

$$\Delta dBA_{1,2} = 10Log_{10}(D_1/D_2)^{1+\alpha} \qquad \textbf{(Line Source)} \qquad \langle 1 \rangle$$

and:

$$\Delta dBA_{1,2} = 10Log_{10}(D_1/D_2)^{2+\alpha} \qquad \textbf{(Point Source)} \qquad \langle 2 \rangle$$

where:

Δ**dBA**$_{1,2}$ is the noise level difference between mic 1 and mic 2; the sign of ΔdBA, + or -, is determined by the noise level at mic 2 with respect to the noise level at mic 1: i.e. if noise level at mic 2 is lower than at mic 1, the sign is -, and vice versa.

$\mathbf{D_1}$ and $\mathbf{D_2}$ are the shortest distance from the source to mic.'s 1 and 2, respectively.

α is the sought after site parameter

Equation <1> (for infinite line source) can be rewritten as:

$$\alpha = [(0.1\Delta dBA_{1,2})/(Log_{10}(D_1/D_2))] - 1 \quad \text{<3>}$$

(D_1 and D_2 **must not** be equal!)

and equation <2> (for stationary point source) as:

$$\alpha = [(0.1\Delta dBA_{1,2})/(Log_{10}(D_1/D_2))] - 2 \quad \text{<4>}$$

(D_1 and D_2 **must not** be equal!)

L_{eq} Data

Equation <3> may be used with the passby L_{eq} data. However, single event L_{eq} data represent a finite line source, since the noise is measured from the point when it rises above ambient levels until it dips below ambient levels. The measured L_{eq} data therefore includes a finite roadway segment "adjustment", which needs to be removed (normalized to an infinite roadway length) before used .

Appendix A derives the relationship between the measured $\Delta dBA_{1,2(fin)}$ for finite roadways and the theoretical $\Delta dBA_{1,2(inf)}$ for infinite roadways:

$$\Delta dBA_{1,2(inf)} = \Delta dBA_{1,2(fin)} + SA_2 - SA_1 \quad \text{<5>}$$

where:

$\mathbf{SA_1}$ and $\mathbf{SA_2}$ are segment adjustments at mic's 1 and 2.

Once $\mathbf{SA_1}$ and $\mathbf{SA_2}$ are known, $\Delta\mathbf{dBA_{1,2(inf)}}$ and α can be calculated using equations <5> and <3>. However, since the segment adjustment at each mic is also a function of α, the process of calculating α includes a "trial and error" iterative process of first estimating α and using the estimate in the calculations of $\mathbf{SA_1}$ and $\mathbf{SA_2}$ (measured Lmax data for mic's 1 and 2 may be used in equation <4> to derive an initial α for calculating $\mathbf{SA_1}$ and $\mathbf{SA_2}$ in equation <5>). Equation <5> may then be used to calculate $\Delta\mathbf{dBA_{1,2(inf)}}$. The latter is then used as an input in equation <3> to calculate α. The resulting α is then used to recalculate $\mathbf{SA_1}$, $\mathbf{SA_2}$, and a new $\Delta\mathbf{dBA_{1,2(inf)}}$. In this project the iterations were continued until $\Delta\mathbf{dBA_{1,2(inf)}}$ was within 0.1 dBA from the previous one.

To calculate $\mathbf{SA_1}$ and $\mathbf{SA_2}$, the Caltrans version of STAMINA2/OPTIMA (SOUND32) computer program's segment adjustment algorithm was modified to allow use with any α. The algorithm was then used in a computer program specially written for the above iterative process which automatically stopped when the 0.1 dBA criterion was met.

$\mathbf{L_{max}}$ Data

Equation <4> is used to calculate α from L_{max} data. The L_{max} is assumed to be an instantaneous noise level from a moving vehicle at its position closest to the mic's, and can therefore be assumed to come from a stationary point source. This α calculation is straight-forward and does not require the iterative process needed with the L_{eq} data, because the effects of segment adjustments are not included.

Crosswind Vector Wind Calculations

In addition to the αs, the crosswind vector of the average wind velocity observed during each passby was calculated from:

$$\mathbf{CW = WS.sin(WA)} \qquad \text{<6>}$$

where:

CW = Crosswind Vector (+ if from source to receiver, - if from receiver to source)

WS = Observed Wind Speed

WA = Wind Angle With Roadway (oriented such that 0° and 180° represent opposite wind directions parallel to the highway, 90° a direction from source to receiver, and 270° from receiver to source).

α Results

The α values were calculated using both methods (L_{eq} and L_{max}) from all vehicle passby data measured at all mic's. Mic data were paired up by equal height and two different distances. Tables C-1 through C-3, Appendix C, show the results of the α calculations using all paired-distance combinations. Only the average values are shown. Examination of these data clearly reveal the following tendencies:

* α values calculated from the measured data were generally higher than the 0.5 soft site value recommended by the FHWA Model.
* α values appeared to increase with distance, and -as expected- decreased as receiver height increased.
* Average α values varied with paired distance combination. Although not shown in Tables C-1 through C-3, individual event α values also varied widely.
* α values for medium trucks appeared to be close to those for autos; however, there appeared to be a significant difference between α values for heavy trucks and those for autos.

* α values based on L_{eq}'s (normalized to an infinite roadway segment per previous discussion) were generally higher than the α values derived from L_{max}'s. The differences appeared to become less as distance from the source increased.

Some of the above findings had already been reported in the interim report which used a portion the data collected at the four single event sites -paired data for the 15 and 61 m (50 and 200 ft) mic positions at a height of 1.5 m (5 ft)- to calculate α values. At that time the initial results were surprising. Although there had been a strong suspicion that 0.5 was too low a value for soft site α in general, values of well over 1 had not been anticipated. Examination of data collected for an earlier Caltrans research project for the evaluation of acoustical design procedures of noise barriers (2) suggested that the average before-barrier soft site α for multiple receivers averaging 41 m (135 ft) from the centerline of nearest lanes of highways was about 0.8 for receiver heights of 1.5 m (5 ft), 0.5 for 4.5 m (15 ft) heights, and 0.3 for 7 m (23 ft) heights. This was based on a "best fit α" that yielded the closest agreement between FHWA Model predictions and noise measurements (as will be shown later, curve-fitted data based on the average distance of 41 m (135 ft) in this study agrees relatively well with the early, crude findings).

Another surprise was the strong distance dependency of both the L_{max}-based and L_{eq}-based α values. The FHWA Model assumes the value to be constant for all distances, and until all the results in this project had been examined, there was no reason to believe that this assumption was incorrect. The initial objective of this reasearch project was to determine more accurate (constant) values for α, which could easily be integrated in existing noise prediction models, with only minor program changes. The confirmed distance-dependency of α seriously undermines the excess attenuation treatment by the FHWA Model. It substantially increases the complexity of integrating the scheme into the FHWA model, and requires sweeping changes to existing algorithms.

The large variations in individual, single event α values (based on L_{eq} as well as L_{max}) were somewhat surprising, although a simple sensitivity study using equations <3> and <4> shows that even noise measurement accuracies of +/- 0.5 dBA in both the L_{eq} and L_{max} can, in worst case situations (paired receiver distance of 15 and 30 m (50 and 100 ft) from the source), and measurement errors in opposite directions- cause a +/- 0.3 variation in α values. Given that single measurements (L_{eq} or L_{max}) often are subjected to acceptable errors of greater than +/- 0.5 dBA, α variations of greater than + or - 0.3 can still be explained from the acceptable accuracy of individual measurements.

The significant differences between heavy truck, and autos/medium truck α values were no surprise. It had long been speculated that these differences existed due to the differences in source heights (and therefore noise path heights) relative to the pavement and surrounding terrain.

The differences between L_{eq} and L_{max} derived α values can most likely be explained by:

* Weakness in the assumption that the measured L_{eq} of a single moving vehicle can be treated as a line source measurement (even after the normalization to an infinite roadway segment). This may explain why the difference between the L_{eq} and L_{max} derived α values tend to diminish with distance.

* Differences between average and instantaneous atmospheric conditions may also cause differences between the α values derived by each method.

Atmospheric Effects on α

Recent studies (4,5,6) have shown the influence of atmospheric wind and temperature gradients on traffic noise measurements at receivers near highways. At approximately 76 m (250 ft) from a highway the difference between a 0 m/s (calm) wind condition and a +2.7 m/s (+6 mph) crosswind averaged 3 dBA for a flat and open grassy field, and appeared to increase with distance, i.e. noise levels at far receivers were affected more than noise levels at near receivers (4). Measured noise level differences between two receivers and resulting α values calculated from these differences will be affected by the crosswind vectors because of this distance dependency.

Temperature gradients are more important for longer distances. However, they will begin to play an important role at distances as close as 122 m (400 ft) (6). As is the case with the wind effects, the distance dependency can be expected to have some effect on the calculated α values.

Air temperature and humidity have an effect on the atmospheric (molecular) absorption rate of sound energy with distance (7). The rates of atmospheric absorptions are also strongly frequency dependent, resulting in frequency spectrum changes and non-linear changes in total noise levels with distance. The effects of these are reflected in the measurements, and therefore the α values calculated from the measurements.

Wind Effects

Wind effects on noise measurements are caused by wind shear (wind velocity gradients). The velocity gradients are created by near-ground frictional forces caused by air moving over the ground, and are responsible for altering the velocity of sound waves relative to the ground. The upper layers of air, travelling at a greater velocity than the lower ones, have an over turning effect on sound pressure waves, causing them to refract towards the ground in the direction of the wind (downwind). In the opposite direction (upwind), however, the sound pressure waves in upper layers of air are slowed down more relative to the ground, causing them to refract upward, away from the ground (upwind). The downwind concentration of noise energy and upwind noise "shadow" account for a respective increase and decrease in noise levels. These effects increase with distance (4,5,6).

For positive crosswind vectors (blowing from source to receiver) noise level differences between near and far receivers will be less than those for negative crosswind vectors (4,5,6). A negative dependency of α values on crosswind vector speeds may thus be expected to exist (i.e. the greater the crosswind vector in the positive direction, the smaller α becomes), and should be strongest for α values calculated from:

* receiver pairs that are separated the furthest, i.e. from receivers nearest to the source paired with those furthest from the source;
* noise data measured over the widest range of crosswind vector speeds;
* source-to-receiver noise paths closest to the ground.

The wind effects on the α results are a concern when attempting to develop α values for various ground characteristics. They potentially could explain some of the fluctuations experienced in the results.

In order to test potential correlations between vector wind speeds and α, the approach was to first test data from receiver pairs incorporating as many of the above factors as possible. Since all sites included the first and the third of the above items, the best data to demonstrate the correlations were data collected at a site with the widest spread in observed crosswind vectors, negative as well as positive.

Figure 9 shows frequency (of occurrence) distributions of observed crosswind vectors, by site. The distributions readily show the following trends:

* At all sites, the positive crosswind vectors tended to be balanced by negative ones, with average crosswind velocities close to zero. The greatest imbalance was found to be at site G-3, where the average vector speed was -0.5 m/s (-1.1 mph), which can still be considered close to zero.

* With few exceptions, the vector wind speeds ranged from -2.2 m/s to +2.2 m/s (-5 mph to +5 mph) , and in most cases from -1.4 m/s to +1.4 m/s (- 3 mph to +3 mph). Site G-4 showed the widest range of observed vector wind speeds:-1.6 to +3.6 m/s (-3.5 to +8.1 mph).

Site G-4, simultaneous 15 and 122 m (50 and 400 ft) auto noise data at a mic height of 1.5 m (5 ft) were selected as the best data set to demonstrate an α vs crosswind (CW) vector speed (in m/s) correlation. Both L_{eq} and L_{max} derived α values - $\alpha_{(Leq)}$ and $\alpha_{(Lmax)}$ - were tested for linear regression. The regression equations and the coefficient of correlation (r) were:

$\alpha_{(Leq)} = 1.33 - 0.183(CW)$; $r = -0.748$, and

$\alpha_{(Lmax)} = 0.95 - 0.246(CW)$; $r = -0.776$

The steepest slope of 0.246 represents a 0.25 change of α, per 1 m/s (2.2 mph) CW. This means that for a + or - 2.2 m/s (5 mph) CW vector, α values calculated from this data set could fluctuate by + or - 0.5 because of differences in wind speeds and directions. However, due to the near-zero balance of CW vectors, the <u>mean</u> α values were not significantly affected. Using the maximum slope of 0.246, for instance, on the data at site G-3 where the greatest CW inbalance, -0.5 m/s (-1.1 mph), was observed, the mean α would be affected by no more than 0.1. The actual regression slope at site G-3, however was 0.08, so that the effect of the inbalance on the mean α would be less than 0.1.

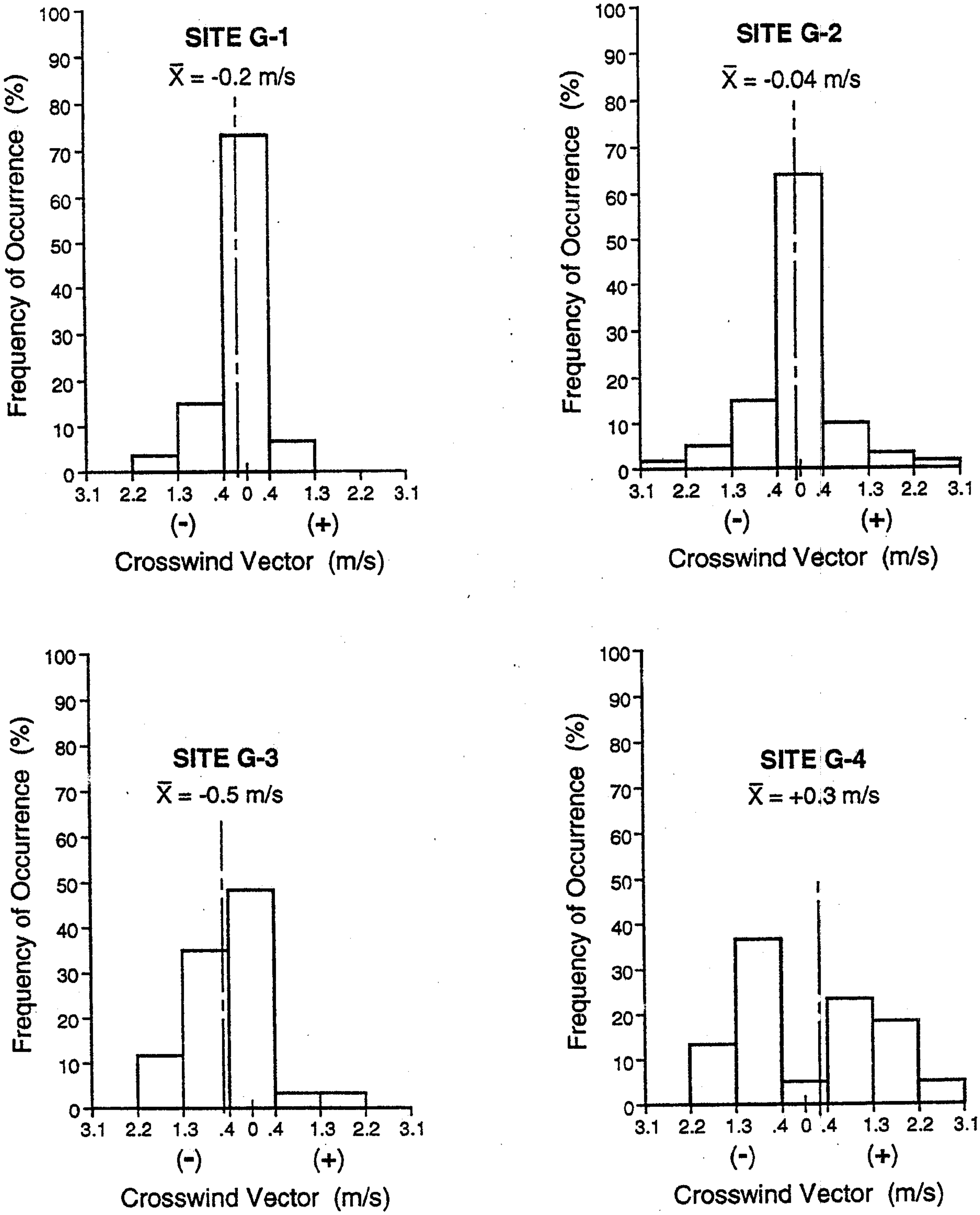


Fig. 9. CROSSWIND VECTOR FREQUENCY DISTRIBUTIONS

With the exception of site G-4 auto data for paired, 1.5 m (5 ft) high mic's, at 15 and 122 m (50 and 400 ft), correlations between α values and CW vectors were generally poor, with coefficients of correlations ranging from 0 to -0.5. Slopes of linear regression lines were not significantly steep in most cases, indicating only weak dependencies of α values on CW vectors. Obvious reasons for the weak dependencies were the lack of range of CW vector speeds, relatively small separation between receivers for mic's 61 m (200 ft or less from the highway), or lack of wind influence at the high mic's.

For these reasons, no attempt was made to adjust the α values to zero wind conditions, nor to compare α values within certain CW vector classifications. The near-zero balance of CW vectors at each site gave further assurance that the mean α vectors would not be biased significantly towards either an upwind or downwind condition.

Temperature Gradients

The effects of temperature gradients (temperature changes with height above ground) on noise levels are especially apparent over longer distances (6).

In a calm atmosphere, temperatures decreasing with height (normal temperature lapse) will affect the noise levels at a receiver in much the same way as if the reeciver were upwind from the source. The lower temperatures in the upper layers cause the sound waves to slow down relative to the lower ones, and refract upwards.

The reverse is true during temperature inversions (temperatures increasing with height) that begin at the ground. These ground inversions are analogous to downwind conditions in that they refract sound waves downward.

An isothermal atmosphere, defined as a condition when air temperatures are the same at any height, does not create any sound wave velocity gradients. This condition can be compared to a calm wind condition.

This study did not measure the differences in temperature at various heights. However, the wind and sky data collected in this project, and available clear sky insolation data (8) for the average latitude of the sites, by day of year and solar time enabled the Principal Investigator to arrive at estimates of atmospheric stability categories, using the Pasquill classifications, modified by Turner (9). These range from class A (extremely unstable, strong lapse conditions) to class D (neutral stability) to class F (moderately stable, ground inversion).

The stability classifications are indications of resistance or enhancement of vertical movement of the air. For dry air, a neutral stability (class D, i.e. no resistance or enhancement of vertical air movement) occurs when the temperature decreases at a rate of about 1° C/100 m (5.4° F/1000 ft) (9). For saturated moist air the lapse rate for neutral stability is about 0.6° C/100 m.(3° F/1000 ft) Unstability occurs when the air temperature decreases at a greater rate than the above; stability occurs when the actual rate of decrease is less than the above rates, when it is isothermal, or when the temperature increases rather than decreases with height (temperature inversion)..

According to the above scheme, an isothermal atmosphere could be considered a class E (slightly stable condition), and an inversion a class F (moderately stable).

Following are estimates of atmospheric stability classes, by site under which the noise measurements were taken:

* Site G-1: Class A (extremely unstable)
* Site G-2: Class A (extremely unstable)
* Site G-3: Class A (extremely unstable)
* Site G-4: Class B (moderately unstable)

The calculated α values in this study are therefore derived from data collected under conditions of extremely to moderately unstable atmosphere. Such conditions occur mostly under calm to light winds, and moderate to strong insolation. Since the FHWA model predicts noise levels for zero wind conditions and insolation is mostly moderate and strong during day time, the calculated α values reflect temperature lapse rates commonly present during the noisiest traffic hour in California. The noisiest hour along highways often occurs during mid-morning or mid-afternoon, when truck volumes usually are highest and traffic is free-flowing.

Because of the day time conditions under which data were collected, the calculated α values may not reflect the proper conditions for nighttime and early morning noise predictions. However, the resulting errors would depend only on the extent of the distance dependency of temperature gradient effects, i.e. the difference in temperature gradient effects at the near and far receiver 15 m and 122 m (50 ft and 400 ft in the worst case) under temperature lapse and inversion conditions. Without temperature gradient data, these differences cannot be estimated.

Atmospheric Absorption

The effects of atmospheric absorptions for the 122 m (400 ft) mic data were estimated to be no greater than 0.5 dBA, using ANSI S1.26 (1978) (7) methodology, observed air temperature and humidity data, and a typical truck noise frequency spectrum (3). No attempt was made to adjust the noise level data at any receiver for atmospheric absorption.

DEVELOPMENT OF NEW α VALUES

Selection and Grouping of α

Tables C-1 through C-3 of Appendix C, show average α values based on L_{eq} and L_{max} measurements, for three vehicle groups, for various paired distance combinations, at for four different sites. Before new α values were developed decisions concerning which data sets to use and how to pool the data had to be made.

L_{eq} vs L_{max} Data

As was previously discussed, the obvious difference between the L_{eq} and L_{max} data was most likely due to the weakness in the assumption that a time-averaged noise measurement of a single moving vehicle can be treated as a line source.

As was shown in the α Calculations section, the α values calculated from L_{eq} data (equations <3> and <5>) caused higher values than those calculated from the L_{max} data (equation <4>). The latter does not rely on the assumption that a moving point source equals a line source, but rather on the more straight-forward assumption that maximum (instantaneous) noise levels equal point sources that are located at a distance closest to the mics. Although a vehicle's size and it's composition of multiple subsources does not make it a true point source, the approximation has been successfully validated (3). For these reasons, the L_{max} derived α values were selected for development of new α values.

Grouping by Meteorological Conditions

Due to the weak α vs wind gradient correlations and the balance in observed positive and negative vector winds, the α data were pooled without regard of wind speed and direction. Nor were they segregated by other atmospheric conditions.

Grouping by Vehicle Type

The α results for autos and medium trucks agreed closely with each other (see Tables C-1 and C-2). For simplicity, the mean α values of the two vehicle types were grouped together. The resulting combined α values for autos and medium trucks were designated $\alpha_{(A,MT)}$.

The mean α values of heavy trucks, however, deviated significantly from those of autos and medium trucks and were therefore kept as a separate set, designated as $\alpha_{(HT)}$.

Selection of Mic Pairs

In the FHWA Model noise levels are first calculated for a reference distance of 50 feet (15 m), then adjusted to the actual receiver distance. The principal investigator used the same convention for the development of new α values with one exception. The exception was the 15 m (50 foot) α, for which the 7.5-15 m (25-50 ft) mic pair data were used. α values at other distances were derived from the following mic pairs: 15-30 m (50-100 ft), 15-61 m (50-200 ft) and 15-122 m (50-400 feet) , for α values at respective distances of 30, 61, and 122m, (100, 200, and 400 ft).

Grouping by Site

A further simplification for the development of new excess attenuation rates was to pool the mean α values of the four sites. Although the initial intent was to develop values for different site characteristics, such a refinement would be difficult to accomplish. The unanticipated distance dependency of the α values, their dependency on height and vehicle type, as well as their large individual variations, would greatly complicate differentiation by site type. Instead, it was decided to opt for α values that would be average for acoustically absorptive ("soft") sites.

Developmental Approaches

The above data pooling and selecting process resulted in α values that were:

* derived from L_{max} noise data;
* derived from data from the following mic distance pairs: 7.5-15, 15-30, 15-61, and 15-122 m (25-50, 50-100, 50-200, and 50-400 ft);
* derived from mics at 0.8, 1.5, 3, and 6 m (2.5, 5, 10, and 20 ft) heights;
* dependent on distance from the source;
* dependent on height above the ground;
* grouped into two vehicle classes: combined autos and medium trucks, and heavy trucks;
* averages for "soft sites";
* for near-calm wind conditions;
* for temperature gradients typical of California, mid-day, often present during the noisiest traffic hours.

The distance variability of the α values suggested that perhaps a linear excess attenuation (LEA) scheme could be used. Excess attenuation using the α parameter is based on a power of ratios of distances, and can therefore be combined with the geometric spreading attenuation. A LEA, however, would be expressed as a dB/foot noise reduction in addition to the geometric spreading.

The relationship between LEA and α is such that a constant value of the LEA would result in an α that increases with distance at a diminishing rate. Examination of the distance dependency of α revealed such a trend.

A constant LEA would obviously be simpler to use over a variable α. For this reason, both a distance variable α and the feasibility of using a LEA were examined for a reference receiver height of 1.5 m (5 ft) above the ground, both for $\alpha_{(A,MT)}$, and for $\alpha_{(HT)}$.

α Vs. Distance, 1.5 m (5 Ft) Reference Receiver Height

Best-fit curves were fit through the combined auto and medium truck mean α data and the heavy truck mean α data vs. distance. In both cases, best fits were obtained with hyperbolic curves of the form:

$$y = a + (b/x)$$

where:

$y = \alpha_{(A,MT)}$ or α
a & b are constants (in this case a is positive, and b is negative)
x = Distance

The hyperbolic equations for $\alpha_{(A,MT)}$ and $\alpha_{(HT)}$ at the 1.5 m (5 ft) reference receiver height are:

$$\alpha_{(A,MT)REF} = 1.55 + (-19.00/\text{Distance, m}) \qquad \text{<7>}$$

Coefficient of Correlation = -0.7779

$$\alpha_{(HT)REF} = 1.18 + (-15.82/\text{Distance, m}) \qquad \text{<8>}$$

Coefficient of Correlation = -0.7515

Figure 10 shows plots of both equations and the data from which they were derived for source-to-receiver distances of 15-122 m (50 to 400 ft).

Linear Excess Attenuation

Under the α scheme in the FHWA Model, total attenuation (TA) with distance can be most simply described as:

TA = Geometric Spreading + Excess Attenuation

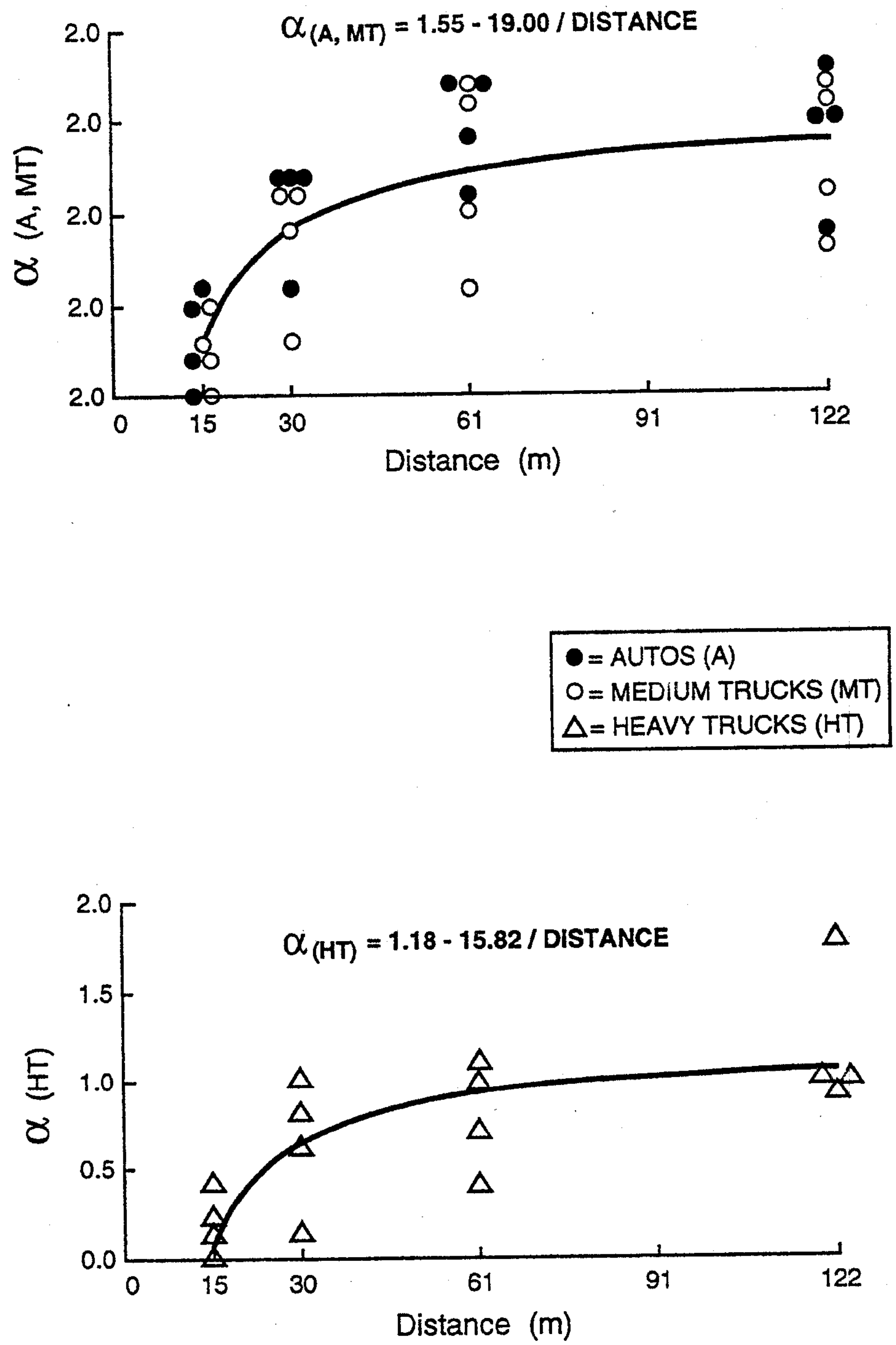


Fig. 10. MEAN α VALUES VS DISTANCE AT FOUR SITES (1.5 m MIC'S)

Equations <1> and <2> in the "α Calculations" section expressed this relationship for a line source and point source. From these equations, the excess attenuation (EA) term can be extracted and expressed as follows:

$$\mathbf{EA = 10\alpha Log_{10}(D_0/D)} \qquad \text{<9>}$$

where: D_0 and D are reference distance and receiver distance

The linear excess attenuation scheme (LEA) investigated included a linear soil parameter, β, expressed in units of dB/ft, beginning at a reference distance of 15 m (50 ft). The LEA was expressed as:

$$\mathbf{LEA = (D - D_0)\beta} \qquad \text{<10>}$$

where,

D = receiver distance
D_0 = reference distance, in this case 15 m (50 ft)
β = linear soil parameter, expressed in units of dB/m

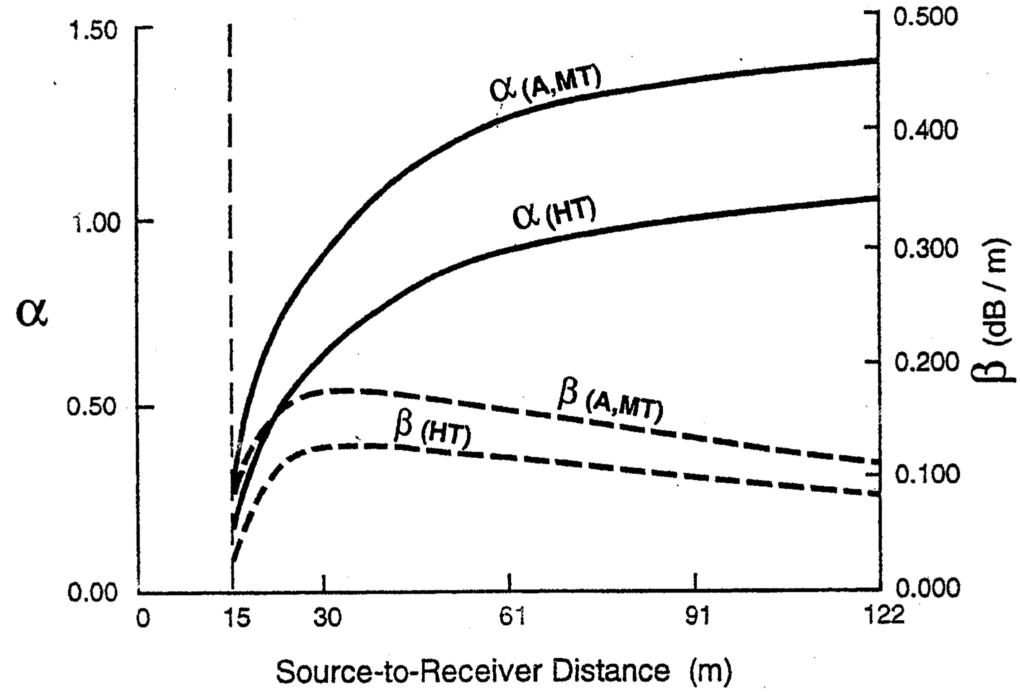
Under the LEA scheme, the LEA for any distance is set equal to the excess attenuation (EA) under the α scheme, or:

$$\mathbf{10\alpha Log_{10}(15/D) = (D - 15)\beta} \qquad \mathbf{(D>15\ m)} \qquad \text{<11>}$$

Equation <11> can be rewritten as:

$$\mathbf{\beta = [10\alpha Log_{10}(15/D)]/(D - 15)} \qquad \mathbf{(D>15\ m)} \qquad \text{<12>}$$

Using the hyperbolic equations for $\alpha_{(A,MT)}$ and $\alpha_{(HT)}$ (equations <7> and <8>), and above equation <12>, β was calculated for various distances and plotted to see whether a constant value could be used. Figure 11 shows the plots of $\alpha_{(A,MT)}$, $\alpha_{(HT)}$, $\beta_{(A,MT)}$ and $\beta_{(HT)}$.



	DISTANCE (m)						
	15	23	30	46	61	91	122
α (A,MT)	0.31	0.72	0.93	1.14	1.24	1.35	1.40
α (HT)	0.14	0.49	0.66	0.83	0.92	1.01	1.05
β (A,MT)	-0.089	-0.184	-0.184	-0.177	-0.164	-0.138	-0.118
β (HT)	-0.039	-0.115	-0.131	-0.131	-0.121	-0.102	-0.089

Fig. 11. DISTANCE DEPENDENCY OF α AND LINEAR EXCESS ATTENUATION (β)

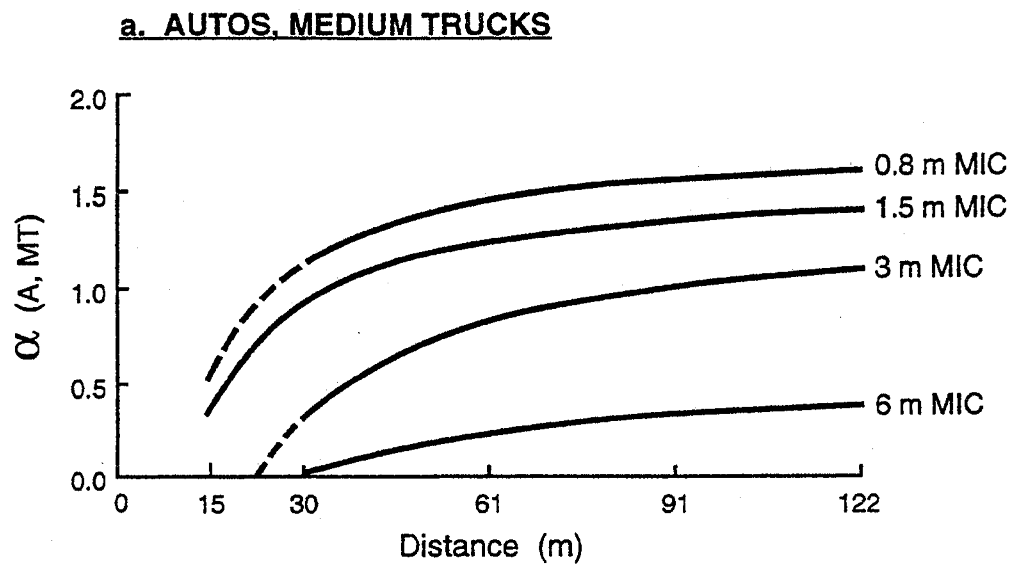
Note that, as was the case with the α values, the β values are also not constant and show a decrease with distance. Therefore, there is no advantage in using the LEA concept over the α scheme, and the LEA approach was abandoned.

α vs Height

Hyperbolic α curves were developed for 2.5, 10 and the 20 foot (0.8, 3, and 6 m) receiver heights in addition to those for the 5 foot (1.5 m) reference height. Figure 12 shows plots of the hyperbolic curves for auto/medium trucks and heavy trucks at the four receiver heights. The hyperbolic equations were used to calculate α values at 15, 30, 61, 122 m (50, 100, 200 and 400 ft) at the four receiver heights for A,MT combined and HT. Next, plots were made of α vs average height for the two vehicle groups.

The average height concept used in the α vs height analysis consists of simply averaging the heights of source relative to the pavement, receiver height above the ground, and noise path above intervening terrain. The process of calculating the average noise path height is shown in Figure 13, for two general cases (without and with noise barrier). However, because of the flat terrain at sites G-1 through G-4 in this study, the average height could simply be calculated by averaging the source and receiver heights.

The receiver heights were fixed by the mic heights. The source heights were more difficult to determine. According to FHWA-RD-77-108, the acoustical centroids for autos are assumed to be located at 0 m, for medium trucks 0.7 m (2.3 ft) and for heavy trucks 2.4 m (8.0 ft) above the roadway pavement. Recent studies in Florida, however, strongly suggest that heavy truck centroids are much lower than 8 feet (2.4 m) (10).



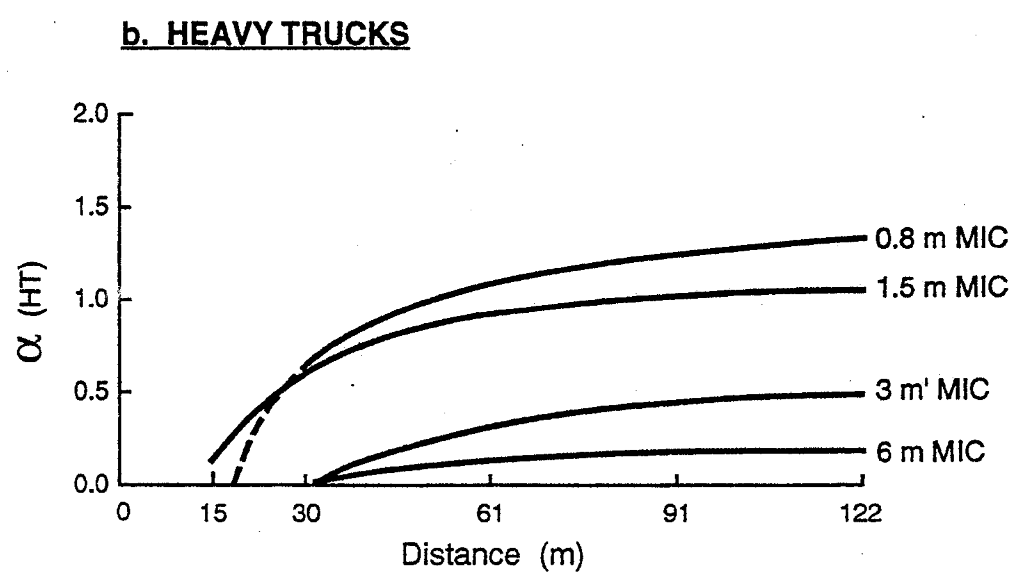
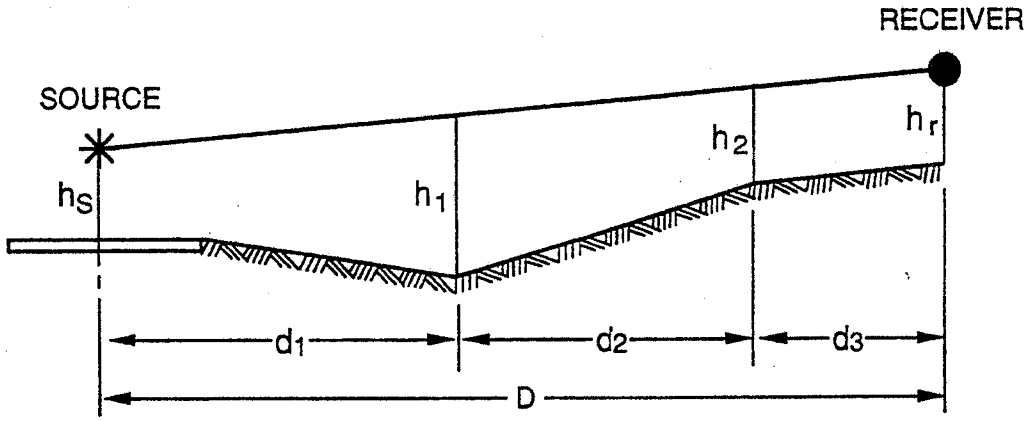
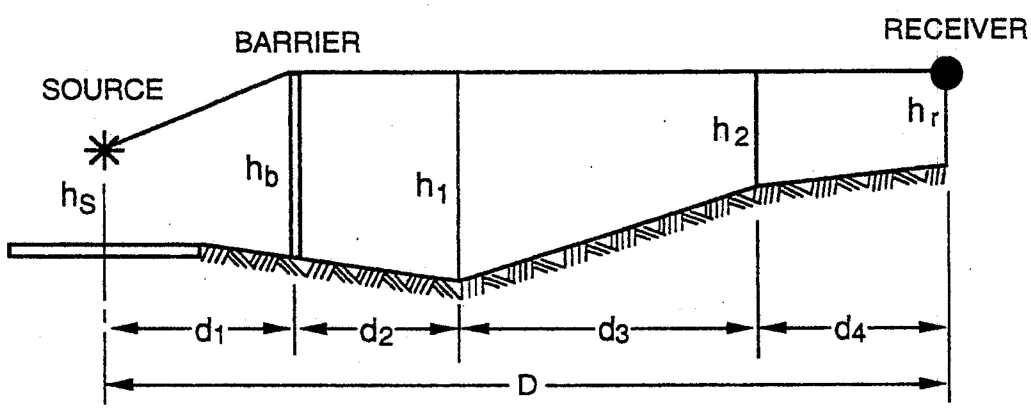


Fig. 12. HYPERBOLIC α CURVES AT FOUR RECEIVER HEIGHTS



$$H_{(AVG)} = \frac{d_1(h_S+h_1) + d_2(h_1+h_2) + d_3(h_2+h_r)}{2D}$$

a. WITHOUT NOISE BARRIER



$$H_{(AVG)} = \frac{d_1(h_S+h_b) + d_2(h_b+h_1) + d_3(h_1+h_2) + d_4(h_2+h_r)}{2D}$$

b. WITH NOISE BARRIER

Fig. 13. AVERAGE NOISE PATH HEIGHT CALCULATION METHOD

In this study, differences in α values for the two vehicle groupings can be explained by differences in <u>average</u> noise path heights alone, if heavy truck centroids are, for simplicity, assumed to be at 1.5 m (5 ft), and automobile/medium truck centroids at 0 m, for distances between 30 and 122 m (100 and 400 ft) from the source. Figure 14 shows plots of calculated α values for distances of 30 - 122 m (100 - 400 ft) vs mean noise path heights. The latter were calculated by averaging the mic height of interest and the source height using 1.5 m (5 ft) for heavy trucks and 0 m for autos and medium trucks.

For the 0.8 m (2.5 ft) mics, the average noise path heights were 0.38 m (1.25 ft) for autos/medium trucks, and 1.14 m (3.75 ft) for heavy trucks. For 1.5 m (5 ft) mics the average heights were 0.8 m (2.5 ft) and 1.5 m (5 ft) respectively; for the 3 m (10 ft) mic heights 1.5 m (5 ft) and 2.3 m (7.5 ft); and for 6 m (20 ft) mic heights 3 m (10 ft) and 3.8 m (12.5 ft) respectively for autos/medium trucks and heavy trucks

Figures 14 also illustrates that the α values for all vehicles vs mean height plots can be described by two straight lines:

Mean α =

= 1.64 - (0.59 Mean Height, m);for Mean Height of 0.4 to 2.3 m **<13>**

and,

= 0.52 - (0.10 Mean Height, m);for Mean Height of 2.3 to 3.8 m **<14>**

Note that both regression lines conveniently intersect at a mean height of 2.3 m (7.5 ft), which coincides with the upper limit of the data set used to derive equation <13> and the lower limit of the data set for equation <14>.

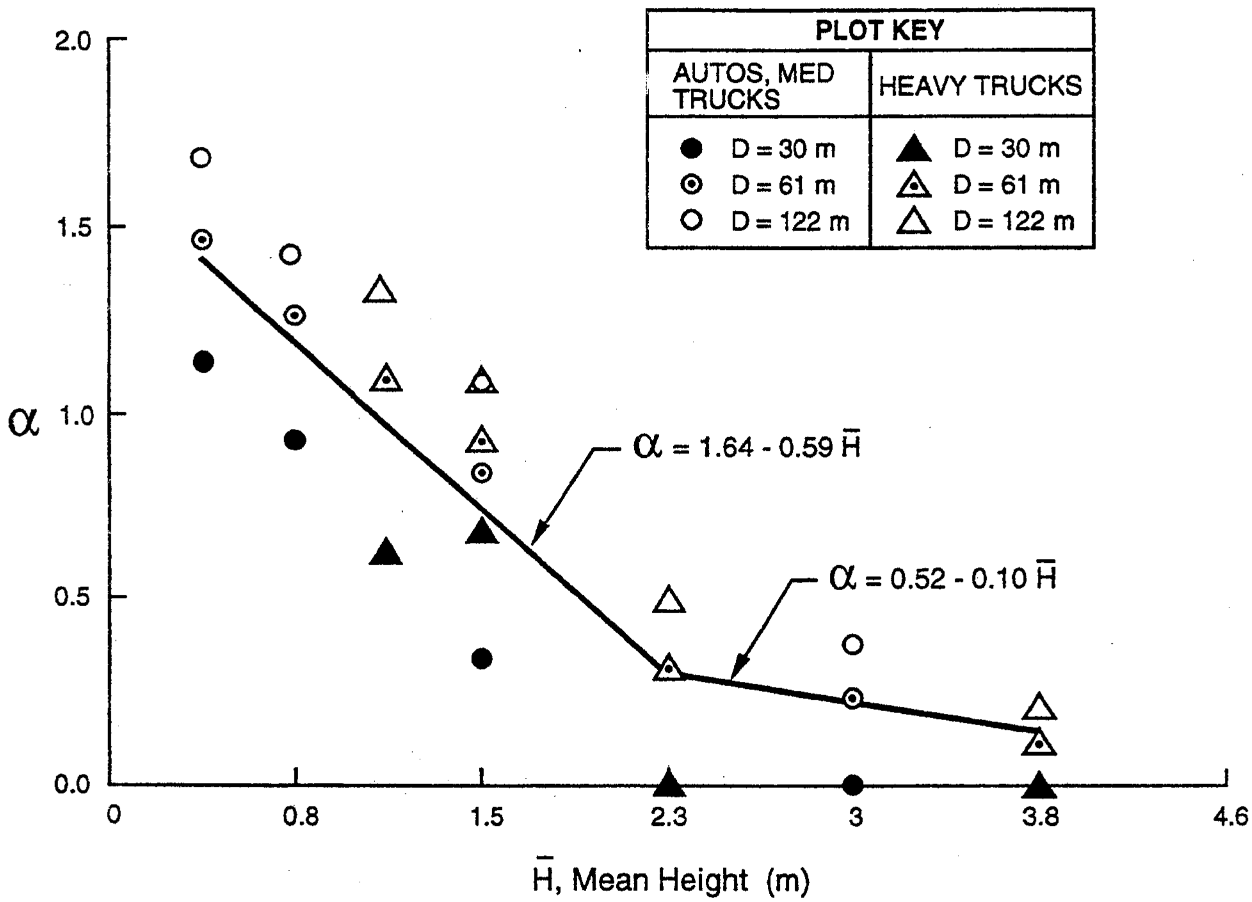


Fig. 14. α VS MEAN HEIGHT PLOTS

Extrapolation of equation <14> to Mean $\alpha = 0$ results in a mean noise path height of about 5 m (17 ft). This average noise path height corresponds with a receiver height of 10.5 m (34 ft) for autos and medium trucks, and 9 m (29 ft) for heavy trucks. This suggests that ground absorption influences noise levels up to receiver heights of more than 30 feet (or about 10 m), much higher than the soft site influence height used in the FHWA Model.

From the regression lines in Figure 14, ratios were calculated with respect to a mean reference height for each vehicle group. These ratios can be applied to the hyperbolic α curves referenced to receiver heights of 1.5 m (5 ft) (equations <7> and <8> in the Developmental Aprroaches section), for α calculation at any height and distance. The mean reference height for the auto/medium truck α curve is 0.8 m (2.5 ft) (average noise path height between source and 1.5 m (5 ft) receiver). For a heavy truck the mean reference height is 1.5 m (5 ft). At these heights the ratios are 1.00.

The ratios as a function of mean noise path height for autos/medium trucks and heavy trucks are:

$\text{Ratio}_{(A,MT)}$ =

= 1.38-[0.49 Mean $\text{Height}_{(A,MT)}$, m]; For Mean H= 0.4 to 2.3 m <15>

= 0.43-[0.10 Mean $\text{Height}_{(A,MT)}$, m]; For Mean H > 2.3 m <16>

$\text{Ratio}_{(HT)}$ =

= 2.21-[0.79 Mean $\text{Height}_{(HT)}$, m]; For Mean H= 0.8 to 2.3 m <17>

= 0.69-[0.13 Mean $\text{Height}_{(HT)}$, m]; For Mean H > 2.3 m <18>

For a given receiver height the relationship between Mean $Height_{(A,MT)}$ and Mean $Height_{(HT)}$ is:

$$\textbf{Mean Height}_{(A,MT)} = \textbf{Mean Height}_{(HT)} - 0.8\ \text{m} \qquad \text{<19>}$$

APPLICATIONS OF NEW α VALUES

α for Any Height and Distance to 150 m (500 Ft)

The entire calculation process of α at any height and distance may be summarized as follows:

$$\alpha_{(A,MT)} = \alpha_{(A,MT)REF} \times \text{Ratio}_{(A,MT)} \qquad \text{<20>}$$

where:

$\alpha_{(A,MT)REF} = 1.55 - (19.00/\text{Distance, m})$

$\text{Ratio}_{(A,MT)}$ = Ratios defined by equations <15> and <16>

$$\alpha_{(HT)} = \alpha_{(HT)REF} \times \text{Ratio}_{(HT)} \qquad \text{<21>}$$

where:

$\alpha_{(HT)REF} = 1.18 - (15.82/\text{Distance, m})$

$\text{Ratio}_{(HT)}$ = Ratios defined by equations <17> and <18>

Figures 15 and 16 summarize the plots and equations necessary to calculate α for any height and distance, to 152 m (500 ft) from a highway, following the above procedure. Note that the curves have been extrapolated from 122 m (400 ft) to 152 m (500 ft). The flatness of the α curves between 61 and 122 m (200 and 400 ft) appears to justify this extrapolation for the convenience of terminating the equations at a convenient distance. In round numbers, 150 m equates to roughly 500 feet, or 0.1 mile, or 0.15 km,: all convenient numbers to remember.

α for Distances Over 150 m (500 Ft)

The α curves lose accuracy beyond 150 m (500 ft). Even if accurate values of α were known for longer distances, atmospheric factors that cannot be accounted for by the FHWA Model would seriously undermine the integrity of noise level predictions.

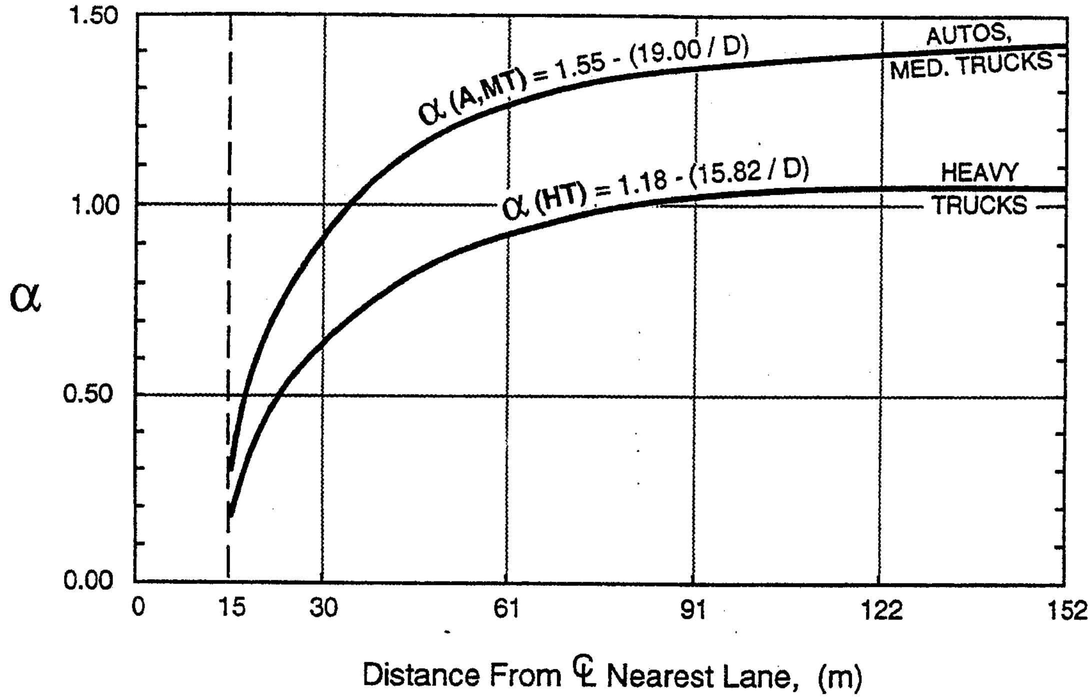


Fig. 15. α VS DISTANCE AT 1.5 m REFERENCE RECEIVER HEIGHT

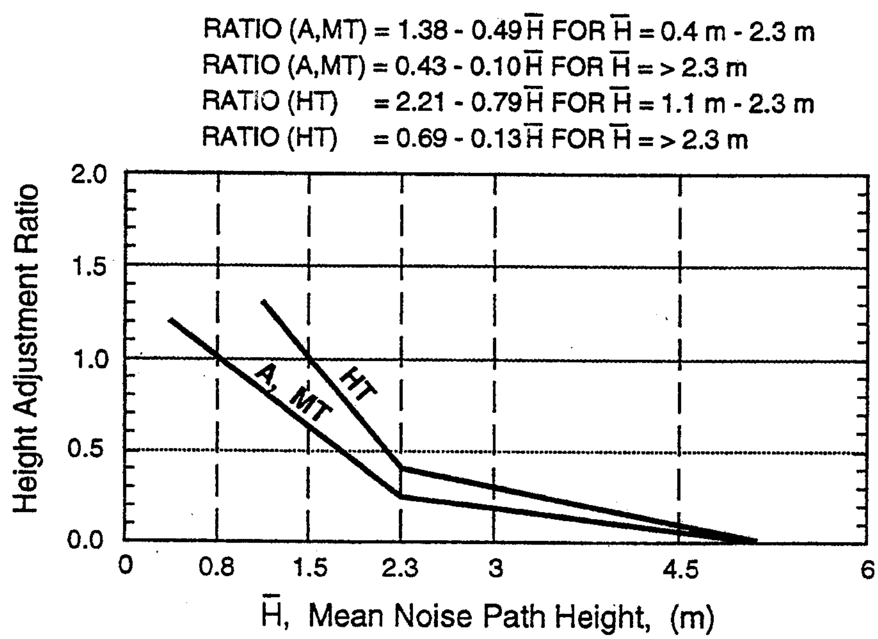


Fig. 16. HEIGHT ADJUSTMENT RATIO VS MEAN HEIGHT

During the search of sites with low ambient noise levels in this research project, as well as during measurements for some special long distance studies by Caltrans, the following combined highway traffic α values (which included atmospheric effects) were observed:

* At 0.15 km (0.1 mi), from this study: 1.25 (average of $\alpha_{(A,MT)}$ and $\alpha_{(HT)}$)
* At 0.55 km (0.34 mi): 1.0
* At 2.4 km (1.5 mi): 0.67
* At 16 km (10 mi): 0.33

The latter was determined at a remote area in the California Central Valley where the only noise source was I-5. By measuring noise levels at 15 m (50 ft) from I-5 and gradually moving away on a cross road, frequently checking noise levels until ambient noise levels (30-35 dBA) were reached 16 km (10 mi) from I-5, the α could be estimated.

According to the rough observations there appears to be a "bulge" in the α vs distance curves, peaking out somewhere between 0.15 and 0.3 km (0.1 and 0.2 mi) from the source. The author has no explanation for why at longer distances the α values appear to decrease again.

Verification of α

A equations <20> and <21> were tested against traffic stream data measured as part of this project at multi-lane verification sites G-1, G-7A, and G-8, and an additional site PB99 used in another research project (4). Figures 17 through 22 show plots of predicted noise levels vs measured values vs microphone location. Figures 17 through 19 include sites without noise barriers; figures 20 through 22 include a site without and with noise barriers. Notice the improvements in noise level predictions when using the

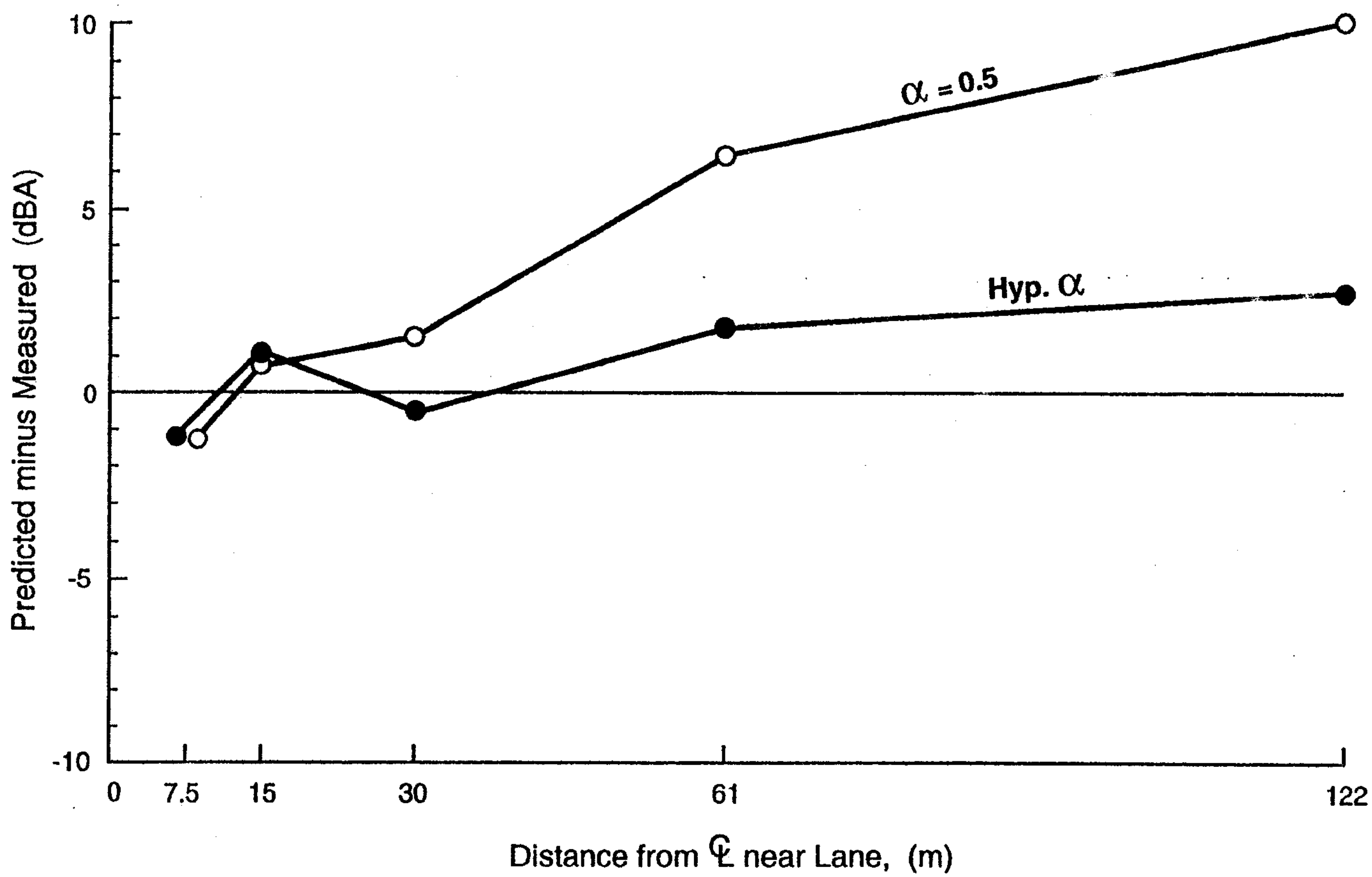


Fig. 17. VERIFICATION, SITE G-1, MICROPHONES 1.5 m HIGH

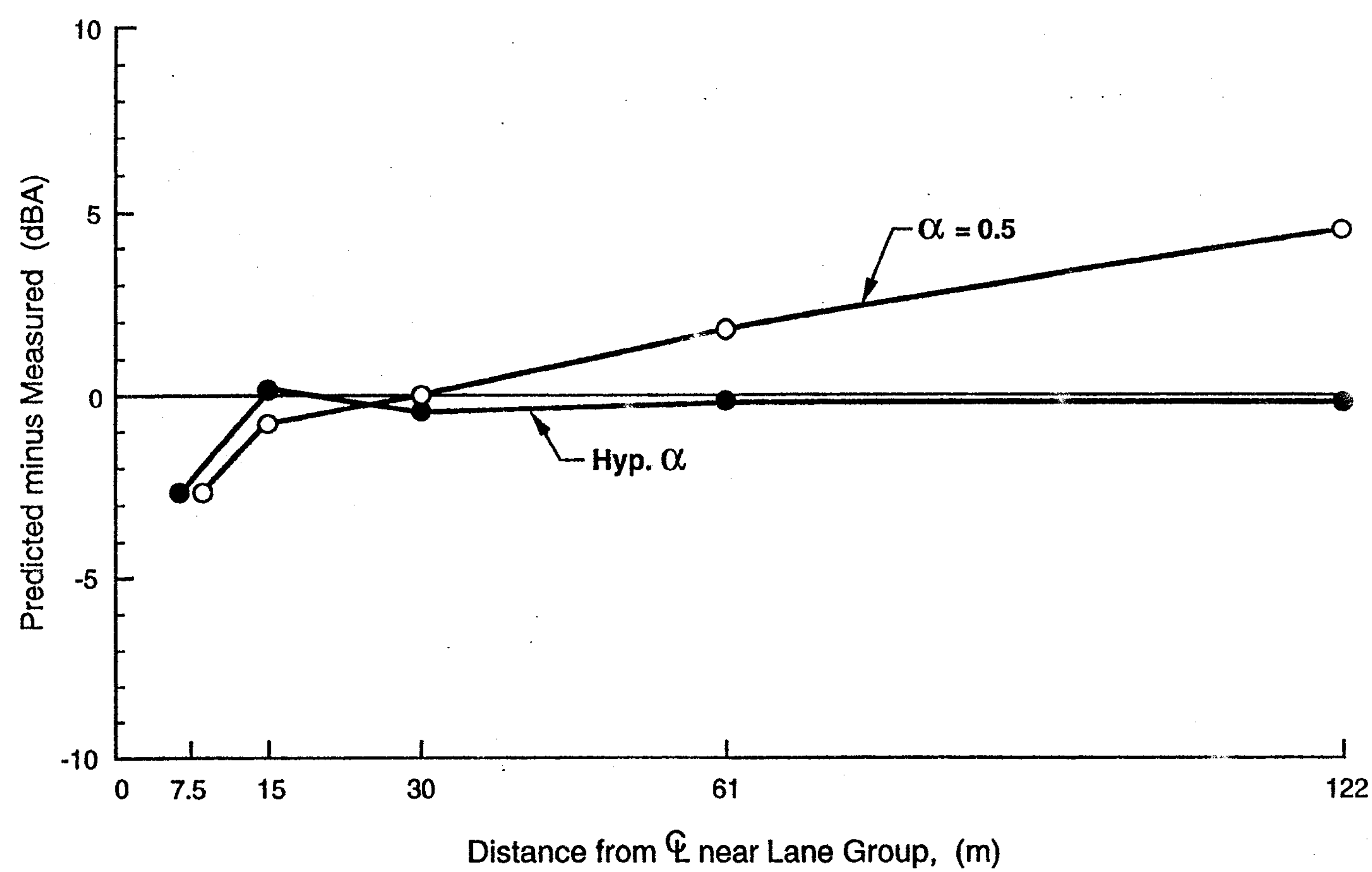


Fig. 18. VERIFICATION, SITE G-7A, MICROPHONES 1.5 m HIGH

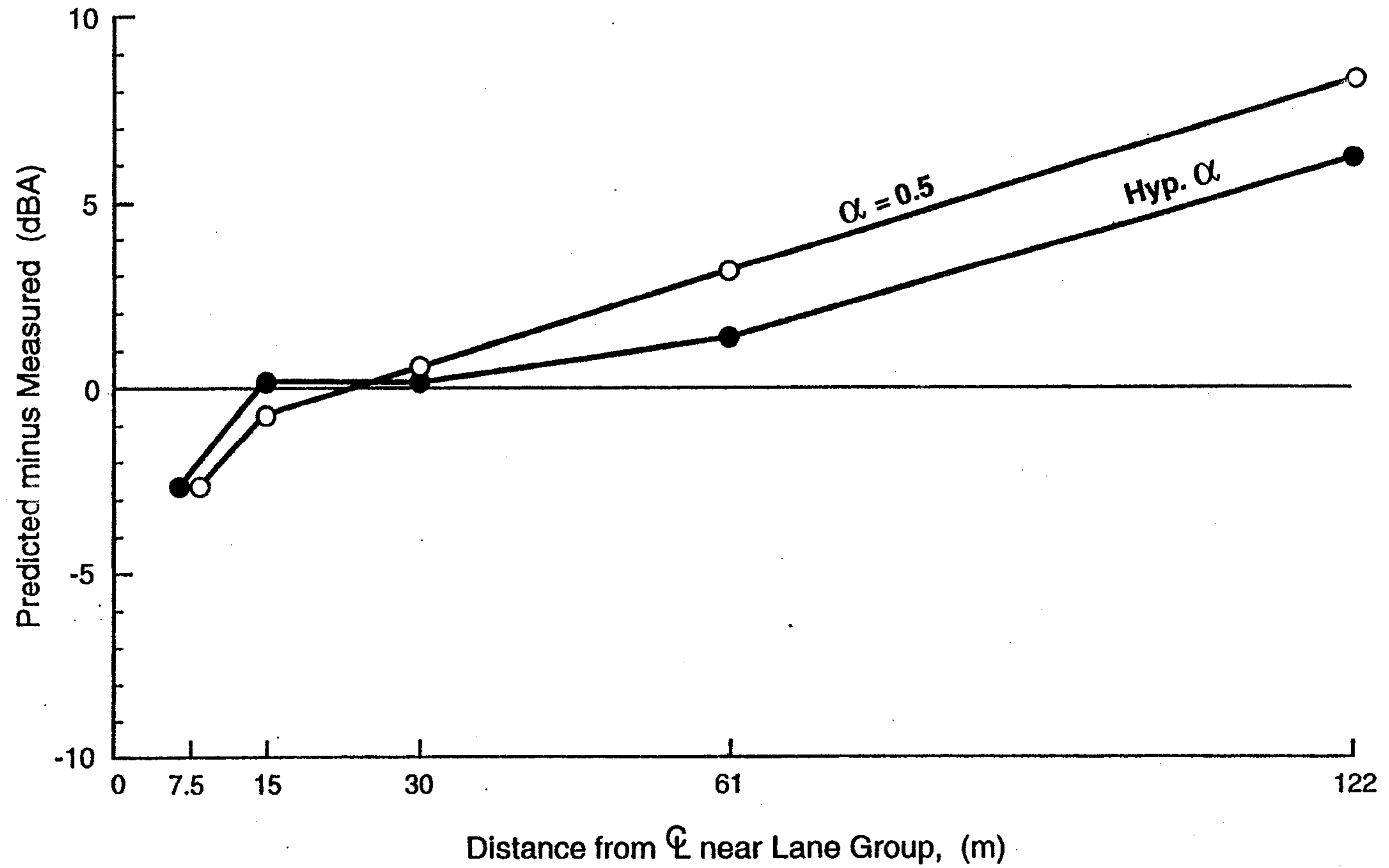


Fig. 19. VERIFICATION, SITE G-8, MICROPHONES 1.5 m HIGH

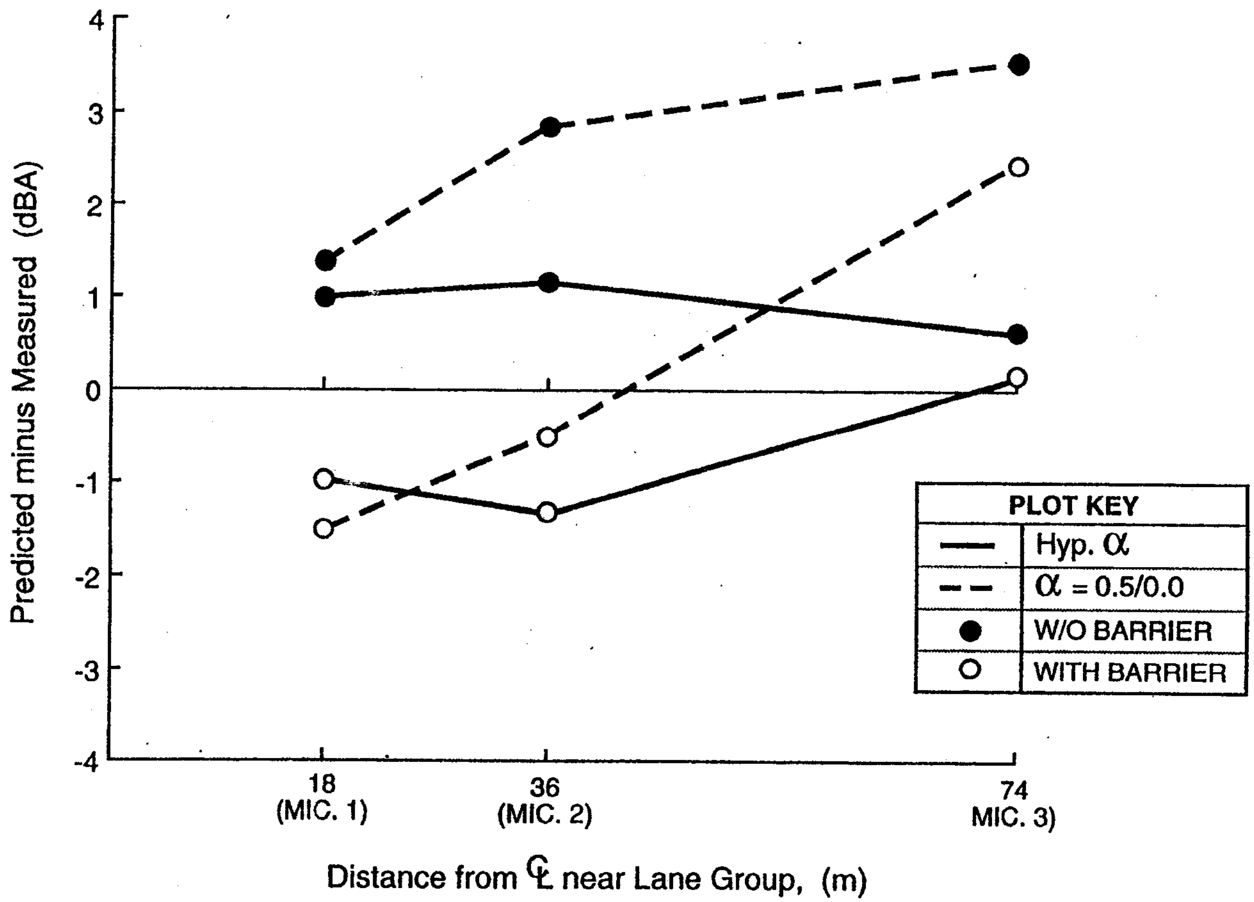


Fig. 20. VERIFICATION, SITE PB99, LOW MICROPHONES (1.5 m HIGH)

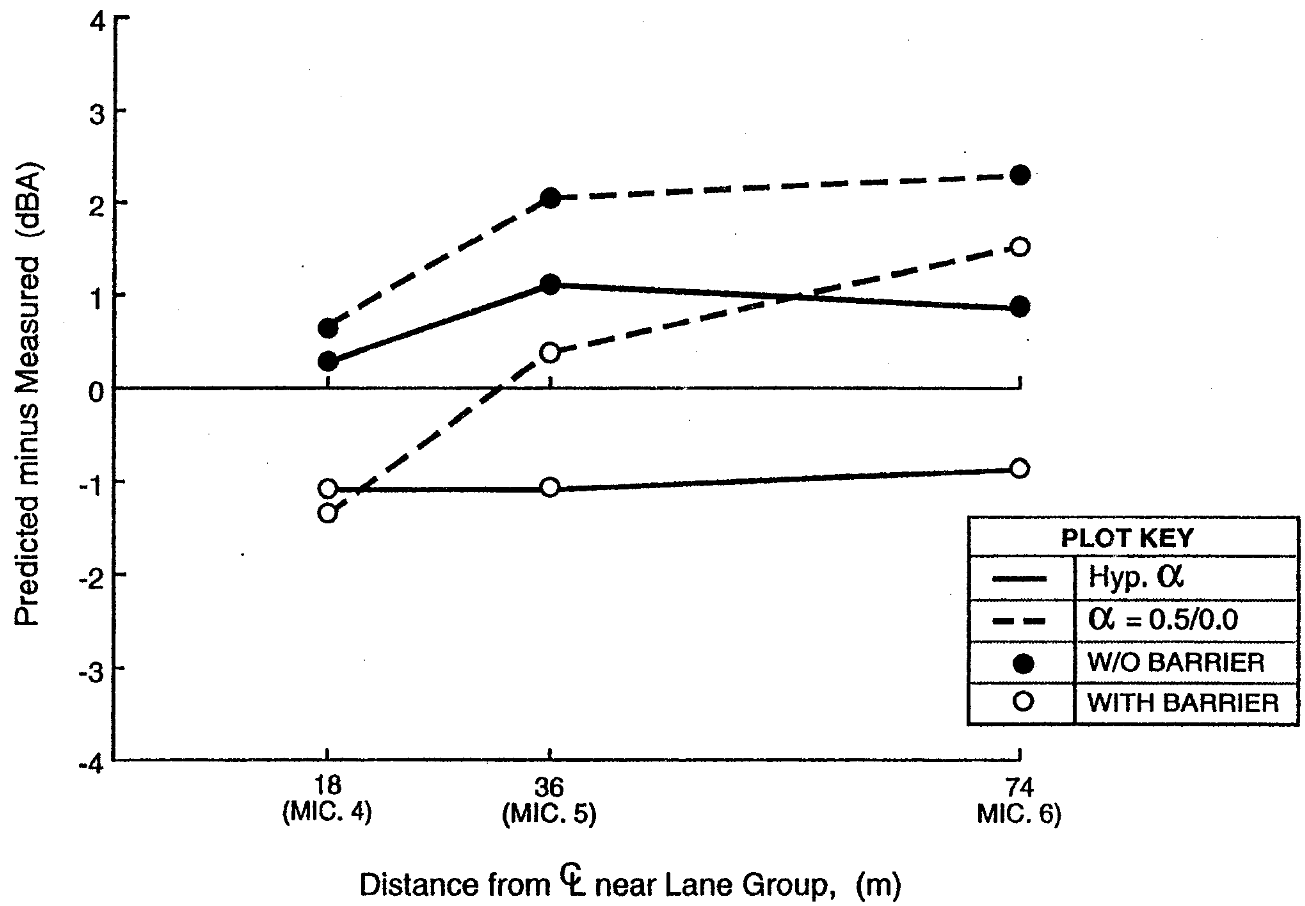


Fig. 21. VERIFICATION, SITE PB99, MIDDLE MICROPHONES (4.5 m HIGH)

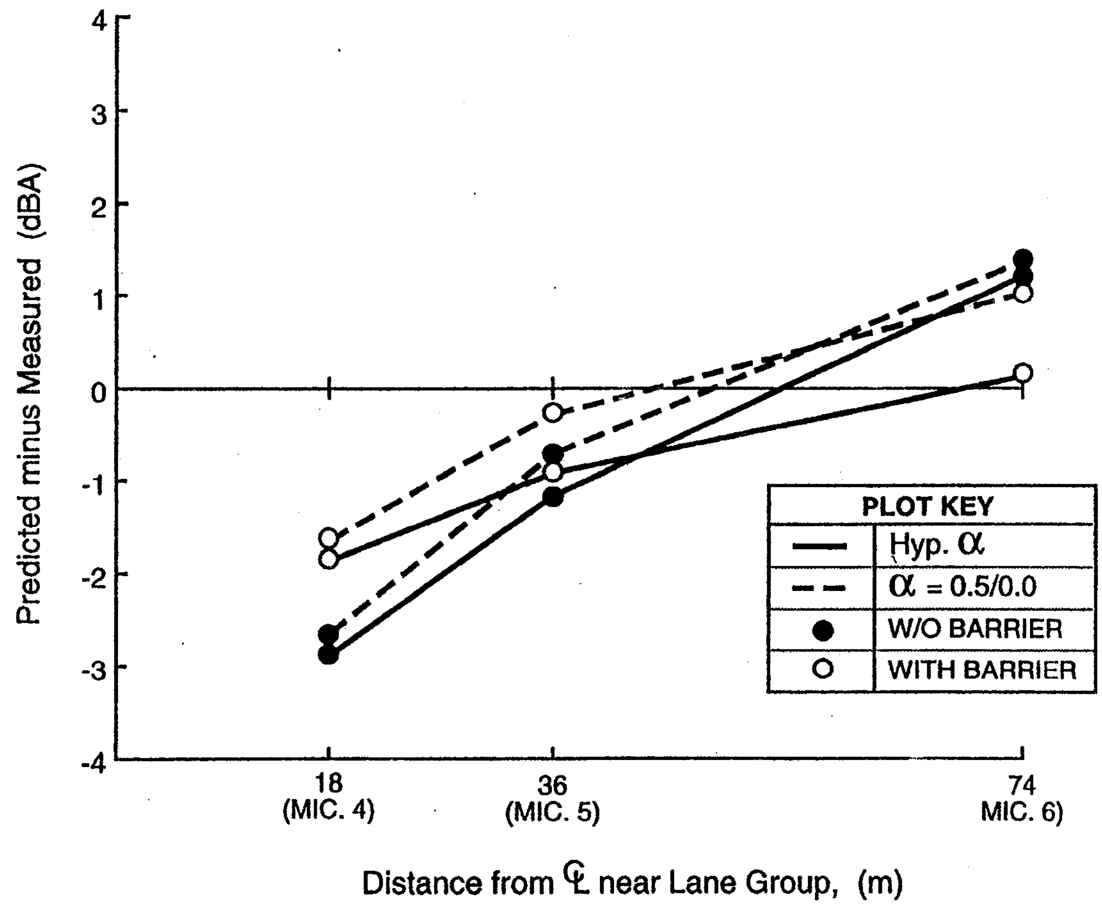


Fig. 22. VERIFICATION, SITE PB99, HIGH MICROPHONES (7 m HIGH)

hyperbolic α values (hyp. α) over the conventional soft site α=0.5 (without noise barriers) and α=0 (with noise barriers).

During the verification analyses it was discovered that better agreement with measured values was obtained for sites G-7A, G-8, and PB99 when, for the purposes of calculating α only, the distances between lane groups and receivers were based on the distance from the CL of the near lane group. Presumably, the α between the near and far lane groups can be considered zero, and the excess attenuation begins at the nearest edge of the traveled way. The actual distances to the lane groups were still used to calculate the total distance attenuation.

Sensitivity Study

A comparison of the sensitivity of hyperbolic α vs the conventional soft site α is shown in Appendix D. The following parameters were tested:

1. Traffic mix, at a reference height, at 30, 61, 122 m (100, 200 and 400 ft) from a highway.
2. Distance from highway at reference heights, using a reference traffic mix.
3. Receiver height at distances of 30, 61, 122 m (100, 200, and 400 ft) from a highway, using the reference traffic mix.
4. Noise barrier heights at a barrier distance of 9 m (30 ft) from a highway, at receiver distances of 30, 61, 122 m (100, 200, and 400 ft), using a reference traffic mix.

In all of the above cases noise levels were predicted using both the hyperbolic α and conventional α. Their differences were also shown. In the barrier case, the barrier insertion losses and their differences are also shown.

CONCLUSIONS

The measured noise level data presented and analyzed in this final report and the interim report published in 1989 (1) lead to the following findings concerning traffic noise attenuation as a function of ground and vegetation.

Vegetative Barriers

In this research project, the term "vegetative barriers" refers to shrubs and trees planted in relatively narrow and dense strips along highways for the primary purpose of landscaping. As used in this report, vegetative barriers do not include the specially designed "green" or "living" noise barriers that incorporate vegetation and structural materials for the specific purpose of noise abatement.

The conclusions and supporting information concerning the incidental effectiveness of shrubs and trees in noise abatement were finalized in the interim report (1). A short summary of the conclusions is repeated in this section and follows.

* A continuous strip of oleander or equivalent shrubs, at least 2.4 m (8 ft) high and 4.5 to 6 m (15 to 20 ft) wide, planted along the edge of a highway shoulder, provides noise attenuations of 1 - 3 dBA at distances of up to 15 m (50 ft) from the rear edge of vegetation.

* A single line of pine trees planted about 7.5 m (25 ft) from the edge of a highway shoulder, 12 m (40 ft) tall, 9 m (30 ft) in diameter, spaced 3 - 6 m (10 - 20 ft) apart, low branches intertwined and touching ground, provides noise attenuations of 0 - 1 dBA at distances of up to 18 m (60 ft) from the rear edge of vegetation.

* A combination of a strip of oleander, planted 11 m (35 ft) from the edge of a highway shoulder, 2.7 m (9 ft) high and 3 - 4.5 m (10 - 15 ft) wide, and redwood trees, equally spaced at 9 m (30 ft) in the oleander strip, 15 m (50 ft) tall and 6 m (20 ft) in diameter, provides noise attenuations of 0 to 1 dBA at distances of up to 21 m (70 ft) from the rear edge of the oleander strip.

* Vegetative barriers (as defined in this study) are not an effective highway noise mitigation measure to use on a routine basis.

* In some borderline cases (to mitigate or not mitigate), thick oleander (at least 4.5 - 6 m, or 15 - 20 ft wide and 3 m, or 10 ft high) may have some value by avoiding conventional noise barrier construction, if adequate right-of-way is available.

* Trimming or removal of shrubs and trees along highways by maintenance or construction does not cause perceptible noise level increases to nearby residences. However, the sudden visibility of highway traffic previously shielded visually by the vegetation, and the possibility of a shift in sound frequencies, may bring on a renewed awareness of the presence of noise sources. This may result in additional noise complaints.

Excess Attenuation, α

The α scheme presently used in the FHWA Model (3) has serious deficiencies. Some of these were recognized from its inception, particularly the discontinuity of the soft site α value with height (3). In reality, α should decrease gradually as the average noise path height between source and receiver with respect to the ground plane increases. This also implies that α varies with vehicle type, due to differences in source heights.

Other previously-known weaknesses were the probable variations in α values due to local site conditions, and lack of field verification. Values for soft site α were expected to fluctuate between near-zero and one, averaging 0.5 (3). This study shows these values to be in excess of 1. However, once accepted for a certain type of terrain, an α value was assumed to be constant with distance, for homogeneous terrain (3). Furthermore, α values based on L_{eq} and L_{max} descriptors are assumed to be equal in the FHWA Model (3).

The major surprise findings in this study were that α values are strongly distant-dependent and that their values often exceeded 1.

The specific conclusions of the excess attenuation portion of this study can be summarized as follows:

* α values for soft sites increase with distance from the source for both the auto/medium truck and heavy truck vehicle groups. The increases tend to follow hyperbolic curves of the form $y = a - b/x$. Specific equations (<7> and <8>) derived from the sites used in this study are shown in the Developmental Approaches section of this report.

* α values for autos and medium trucks are similar and may be grouped together; heavy truck αs, however, are significantly different and should be seperate.

* Average α values for soft sites are generally higher than the 0.5 value recommended in the FHWA Model (3) and, depending on the distance from the source, range from 0.34 at 15 m (50 ft) to 1.43 at 150 m (500 ft) for autos/medium trucks, and from 0.14 at 15 m (50 ft) to 1.08 at 150 m (500 ft) for heavy trucks.

* α values based on the L_{eq} descriptor were higher than those based on the L_{max} (the FHWA Model assumes both to be the same). The differences appear to decrease with distance.

* Average α values varied with paired distance combinations.

* α values decreased with average heights of the sound path above the ground. For the purpose of calculating average heights, heavy truck centroid heights of 1.5 m (5 ft) above the pavement and auto/medium truck centroids height of 0 m appear to yield the most consistent α results with respect to sound path height.

* α values of both vehicle groups can be adjusted from a reference height to the actual height by a ratio that can be expressed as a linear regression equations of the form $y = a - bx$. Specific equations (<15> through <18>) are shown in the Developmental Approaches section.

* α values developed in this study showed improvements (averaging from 2 to 7.5 dBA at 122 m (400 ft) from the nearest highway lanes) in model predicted noise levels when they replaced the conventional soft site α in field verifications.

* Field verification also showed that the developed α values could be used with noise barriers when the average sound path heights were corrected as a result of the barrier presence, also resulting in considerable model prediction improvements (up to 3 dBA at 74 m (243 ft) from the nearest highway lanes, shielded by a 4.3 m (14 ft) high barrier).

* The α results in this report are consistent with the observed deficiencies of soft site α values reported in a 1981 federally-funded study performed by Caltrans (2), for the same range of conditions.

RECOMMENDATIONS

The conclusions presented in this report illustrate the deficiencies in the α scheme as it was intended to be used in the FHWA Model set forth in FHWA-RD-77-108 (3). Any attempts to correct for these deficiencies in the various FHWA Model-based computer programs used nationally or within California (STAMINA2.0/OPTIMA, SOUND32, LEQV2, etc.) will make these programs very cumbersome to use.

One of the main problems in using the existing computer programs with respect to α is that the programs do not recognize terrain information that can be used to calculate sound path heights above the ground. These must be estimated and averaged by the user over each segment. Each source/receiver pair will have different distances and heights on which α is dependent. The user is therefore faced with a dilemma between compromising accuracy (to the point of unacceptibility) and the addition of much preliminary work to calculate the "correct" α (if this is possible) for each source/receiver pair, in each roadway and barrier segment.

This author recommends that the α scheme be abandoned in future noise prediction models and associated computer software. The α scheme was useful in the early days of noise prediction because it was the best methodology available. For short distances (less than 30 m, or 100 ft) from the source the FHWA Model's α scheme can still be used satisfactorily. However, for longer distances the α scheme falls apart rapidly.

Future noise prediction models should incorporate terrain information and sophisticated algorithms describing sound wave/ground plane interaction as a continuous function with height.

Until such models are developed, the author recommends a "stop-gap" measure that will improve the overall accuracy of FHWA Model results. Without trying to incorporate the empirically derived hyperbolic α curves in the various computer versions of the FHWA Model, the following soft site correction values in dBA may be applied to receiver noise levels, based on source/receiver distance and a user judgment of average sound path height above the ground.

CORRECTION TO RECEIVER NOISE LEVEL, dBA
(From Figures 15 and 16)

Average Height, m (ft)	Distance <30 m (100 ft)	30-61 m (100-200 ft)	61-150 m (200-500 ft)
< 3 (10)	0	-2	-4
3-6 (10-20)	0	-1	-2
> 6 (20)	0	0	0

The above correction table is based on an average traffic mix of 8% Heavy Trucks, 4% Medium Trucks and 88% Autos. For this typical traffic mix, the heavy truck noise contribution roughly equals that of the autos and medium trucks, and the α values of both vehicle categories can be averaged at any distance and height. The corrections should be applied to all calculations using the conventional soft site α treatment in the FHWA Model ($\alpha = 0.5$ without a barrier for sound path heights of less than 3 m (10 ft) and 0 for greater heights, and $\alpha = 0$ for barriers providing more attenuation than $\alpha = 0.5$). The corrections are based on average α values for distance and height ranges shown, and, because of this, their accuracy cannot be better than within 2 dBA. The corrections should still be conservative, i.e. they should generally still yield a slight over prediction of the model.

For the purposes of estimating average sound path heights a 0.8 m (2.5 ft) traffic source height above pavement should be used with the average height calculation method shown in Figure 13. The 0.8 m (2.5 ft) source height represents the average of 0 and 1.5 m (0 and 5 ft) for autos/medium truck and heavy truck noise propagation discussed in the "Development of New α Values" chapter (α vs. Height section) of this report.

IMPLEMENTATION

Upon approval of the FHWA and after in-house consultation with appropriate units within Caltrans, the above stop-gap recommendations will be implemented by memorandum to all Caltrans Districts and consultants performing noise analyses under Caltrans contracts.

The author is aware that the FHWA is developing a new state-of-the-art noise prediction model under contract. The model, scheduled to be completed and tested in several years, will include an excess attenuation treatment that will be different from the α scheme presently used. Until the model becomes available strong consideration should be given to approving the above stop-gap corrections for implementation.

BENEFITS

The 1981 Federally-funded research project titled: "Evaluation of Noise Barriers", performed by Caltrans (2) revealed that the FHWA Model over predicted noise levels by 3 - 4 dBA at average distances of 41 m (135 ft) from highways. Two major factors were suspected to be responsible: emission levels (independent of distance from the source) and attenuation rates (distance dependent).

The development and implementation of the California Vehicle Noise Emission Levels in 1985 (11), finalized in 1987 (12) was the first stage in correcting the deficiencies in the FHWA Model. Improvements of 1.5 -2 dBA (independent of distance from the source) were realized after implementation, i.e. average FHWA Model overpredictions (at 41 m, or 135 ft) were now reduced to 1 - 2.5 dBA.

The results of this research project indicate that average over predictions of 2 dBA at 30-61 m (100-200 ft) can be attributed to using the soft site attenuation rate value prescribed by the FHWA Model. This is consistent with the earlier conclusion of the over prediction of 1 - 2.5 dBA attributed to excess attenuation descrepancies in the FHWA Model.

If the "stop-gap" suggestions in the "Recommendations" section are followed, noise level predictions at distances between 30 and 61 m (100 and 200 ft) from highways will be reduced by 2 dBA. This would affect noise impact predictions of new facilities where FHWA Model noise predictions cannot be "calibrated" by measurements of existing conditions.

The financial consequences of correcting the Model by 2 dBA for predictions in the 30-61 m (100 - 200 ft) range can be summarized as follows.

A 2 dBA reduction in noise prediction would reduce noise barrier heights by 0.6-1.2 m (2-4 ft) which translates into an average of 0.9 m (3 ft) x 1609 m (5,280 ft) = 1472 sq. m (15,840 square ft) per 1.6 km (1 mi) of noise barrier. Assuming an average of 16 km (10 mi) per year noise barrier construction for new highway facilities in California, half of which have first-tier design receivers at distances of 30 - 61 m (100 - 200 ft), the yearly savings would be 8 km (5 mi) x 920 sq.m/km (15,840 sq.ft/mi) x $ 161.50/sq.m ($ 15/sq.ft) = $ 1,188,000 per year (say $ 1,000,000/year).

The above saving does not take into consideration additional savings from not having to build a noise barrier in the first place, due to reduction of the noise impact by 2 dBA.

A less tangible, but potentially more important benefit of this research is that the data can, and probably will, be used to verify improved algorithms that will be used in a new highway traffic noise prediction model and software contracted out by FHWA to replace the currently used FHWA Model (3)-based computer programs STAMINA2/OPTIMA and SOUND32 (used by Caltrans). The new model and software are scheduled to be completed in the summer of 1995, and will be introduced to the states in subsequent years. Eventually, the new model will be the only FHWA approved noise prediction model, and California will have had the privilage of providing considerable input. Current plans are for California Vehicle (Calveno) Noise Emission Levels (12) to be the backbone for Reference Energy Mean Emission Levels (REMELS) used by the model. Coupled with the noise propagation data gathered for this research project, the new model will be especially suited for this state, by virtue of California data inputs.

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12. Hendriks, R.W., "California Vehicle Noise Emission Levels, Final Report", Report No. FHWA/CA/TL-87/03, California Department of Transportation, Office of Transportation Laboratory, Sacramento, California, January 1987.

APPENDIX A

RESEARCH APPROACH

RELATIONSHIP BETWEEN

THE HOURLY L_{eq} AND THE PASSBY L_{eq}

OF A SINGLE TYPICAL HEAVY TRUCK AT 50 FEET

(VEHICLE SPEED = 55 MPH)

FHWA MODEL (3):

$$L_{eq}(h)_{HT} = (L_0)_{E,HT} + 10\mathrm{Log}_{10}(N_{HT} \cdot \pi \cdot D_0/S_i \cdot T) +$$

$$+10\mathrm{Log}_{10}(D_0/D)^{1+\alpha} + 10\mathrm{Log}_{10}(\,\psi_\alpha(\,\phi_1\,,\,\phi_2\,)/\,\pi\,) \qquad \text{<A-1>}$$

where:

$L_{eq}(h)_{HT}$ = hourly L_{eq} of N heavy trucks (HT) (in this case N=1) =

=Reference Energy Mean Emission Level of HT
+ traffic flow adjustment for N HT/hour (here N=1)
+ distance adjustment
+ roadway segment adjustment

In Figure A-1 (next page), assuming site parameter α = 1.0 (very absorptive site), and using California Vehicle Noise (Calveno) Emission Levels:

$L_{eq}(h)_{HT}$ = 49.0 dBA

For $L_{eq}(t)$, where t is the duration of the truck's passby in seconds:

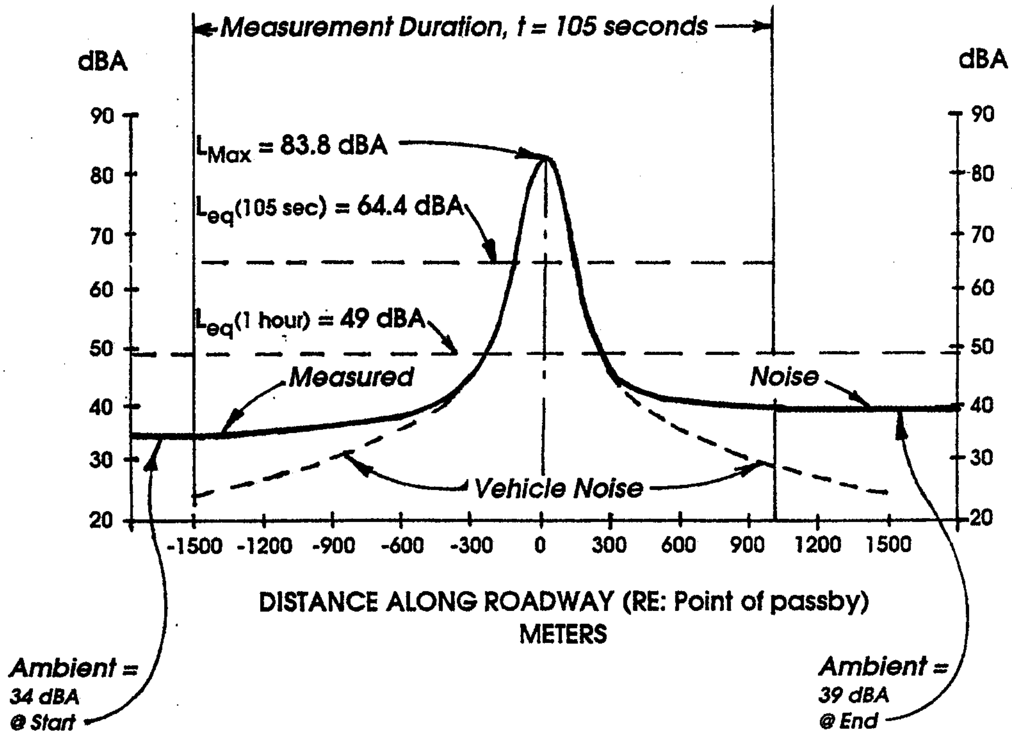
$$L_{eq}(t)_{HT} = L_{eq}(h)_{HT} + 10\mathrm{Log}_{10}(3600/t) \qquad \text{<A-2>}$$

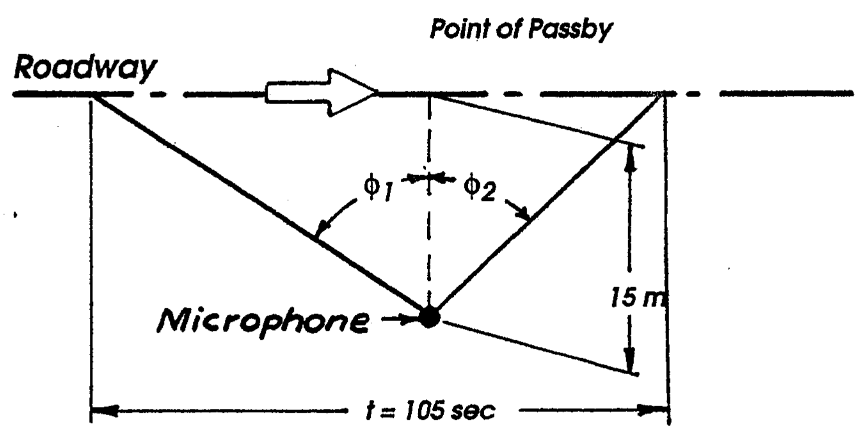
Using the example below (Figure A-1), for a passby duration of 105 seconds, the L_{eq} is calculated as follows:

$$L_{eq}(105)_{HT} = L_{eq}(h)_{HT} + 10\mathrm{Log}_{10}(3600\,/105)$$

$$= 49.0 + 15.4 = 64.4 \text{ dBA}$$

Figure A-1. Relationship Between L_{Max}, $L_{eq(t)}$, and $L_{eq(h)}$ of a Single Heavy Truck Pass at 88 km/hr (55 Mph), Measured at 15 m (50 Feet) from Center Line of Travel





Roadway Segment $= \Delta\phi = \phi_2 - (-\phi_1) = \phi_1 + \phi_2$.

PROCEDURE FOR NORMALIZING MEASURED SINGLE VEHICLE PASSBY NOISE LEVEL DIFFERENCES BETWEEN TWO RECEIVERS, FROM A FINITE TO AN INFINITE ROADWAY

Using equation <A-1> from page A-2, for the noise level difference between Receivers 1 and 2, located at distances D_1 and D_2 from a roadway (see Figure A-2, next page):

$$L_{eq}(h)@1 - L_{eq}(h)@2 =$$

$$10Log_{10}(D_0/D_1)^{1+\alpha} - 10Log_{10}(D_0/D_2)^{1+\alpha} +$$

$$+ 10Log_{10}(\ \psi_\alpha\ (\ \phi_1,\phi_2\ )/\ \pi\ ) - 10Log_{10}(\ \psi_\alpha\ (\ \phi_3,\phi_4\ )/\ \pi\ )$$

Let: $L_{eq}(h)@1 - L_{eq}(h)@2 = \Delta dBA_{1,2(fin)}$ and:

Let: $10Log_{10}(\ \psi_\alpha\ (\ \phi_1,\phi_2\ )/\ \pi\ ) = SA_1$ (Segment Adjustment at Rec. 1), and:

Let: $10Log_{10}(\ \psi_\alpha\ (\ \phi_3,\phi_4\ )/\ \pi\ ) = SA_2$ (Segment Adjustment at Rec. 2)

SA_1, and SA_2 can be calculated using STAMINA2.0 segment adjustment algorithm, modified for any α.

Then:

$$\Delta dBA_{1,2(fin)} = 10Log_{10}(D_0/D_1)^{1+\alpha} - 10Log_{10}(D_0/D_2)^{1+\alpha} + SA_1 - SA_2 =$$

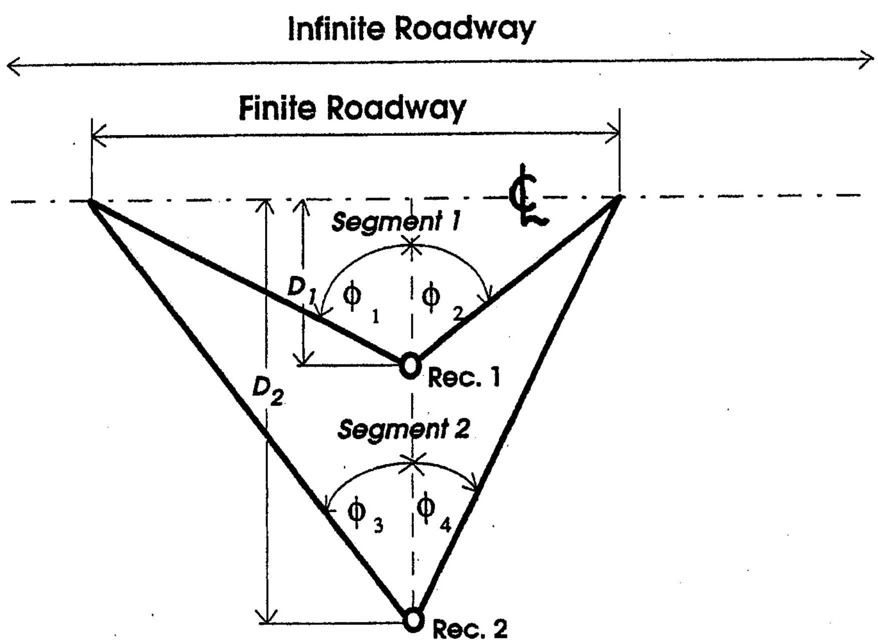
$$\mathbf{\Delta dBA_{1,2(fin)} = 10Log_{10}(D_2/D_1)^{1+\alpha} + SA_1 - SA_2}$$ **<A-3>**

To normalize measured $\Delta dBA_{1,2(fin)}$ for <u>finite</u> roadway to $\Delta dBA_{1,2(inf)}$ for <u>infinite</u> roadway, segment adjustments must be removed, i.e. the process must be reversed:

$$\mathbf{\Delta dBA_{1,2(inf)} = \Delta dBA_{1,2(fin)} + SA_2 - SA_1}$$ **<A-4>**

The segment adjustments SA_1 and SA_2 are dependent on the site parameter α. Therefore, α needs to be known or estimated before equation <A-4> can be solved.

Figure A-2. Normalizing Noise Level Differences (L_{eq}) From Finite to Infinite Roadway



Δ $dBA_{1,2(fin)} = L_{eq}(h)$ @ Rec. 1 - $L_{eq}(h)$ @ Rec.2

Δ $dBA_{1,2(inf)} = \Delta$ $dBA_{1,2(fin)} + SA_2 - SA_1$

Where: SA_2 and SA_1 are adjustments for Sements 1 and 2 respectively

CALCULATION OF SITE PARAMETER α FROM THE DIFFERENCE IN NOISE LEVELS BETWEEN TWO RECEIVERS LOCATED AT DIFFERENT DISTANCES FROM A NOISE SOURCE

Single Vehicle Passby L_{eq} Data:

Substituting equation <A-3> in <A-4> (see previous pages), equation <A-4> becomes:

$$\Delta dBA_{1,2(inf)} = 10Log_{10}(D_2/D_1)^{1+\alpha} \qquad \text{<A-5>}$$

Thus, from L_{eq} differences of a single vehicle passby (time integrated noise measurements, or simulated finite line source) - normalized to an infinite line source - the site parameter α can be calculated by rewriting equation <A-5>:

$$\alpha = [0.1(\Delta dBA_{1,2(inf)})/Log_{10}(D_2/D_1)] - 1 \qquad \text{<A-6>}$$

(D_1 and D_2 **must not** equal!)

The process of calculating α from $\Delta dBA_{1,2(fin)}$ requires an iterative process using equations <A-4> and <A-6>. The process starts with an estimate of α, (a good starting point is α derived from L_{max} data from following equation <A-8>) to calculate SA_1 and SA_2 (see previous pages). $\Delta dBA_{1,2(inf)}$ can then be calculated from equation <A-4>, and a new α can be derived from <A-6>. The new α is then used to calculate a new SA_1 and SA_2, and subsequently a new $\Delta dBA_{1,2(inf)}$. The process is repeated until $\Delta dBA_{1,2(inf)}$ changes less than some previously set criterion (e.g. 0.1 dBA used in this study).

Single Vehicle L_{max} Data:

The L_{max} difference between mic 1 and mic 2 ($\Delta dBA_{1,2}$) of a single vehicle passby can be expressed by the following equation <A-7>. The equation assumes that the L_{max} is the instantaneous noise level from a point source located at the closest distances from mic's 1 and 2.

$$\Delta \mathbf{dBA}_{1,2} = 10\mathbf{Log}_{10}(\mathbf{D}_2/\mathbf{D}_1)^{2+\alpha} \qquad \text{<A-7>}$$

To solve for α, equation <A-7> may be rewritten as:

$$\alpha = [0.1(\Delta \mathbf{dBA}_{1,2})/\mathbf{Log}_{10}(\mathbf{D}_2/\mathbf{D}_1)] - 2 \qquad \text{<A-8>}$$

(D_1 and D_2 **must not** equal!)

Theoretically, the α values calculated from the L_{eq} and L_{max} data should be the same, assuming that:

1. The terrain at the site is perfectly homogeneous
2. The time integrated noise measurement (L_{eq}) of a single moving vehicle attenuates with distance at the same rate as a line source
3. The L_{max} noise measurement of a moving vehicle attenuates with distance as a point source

APPENDIX B

SITE CROSS SECTIONS AND EXAMPLES OF MEASUREMENT DATA

Figure B-1 Cross Section of Site G-1 "KESTERSON"

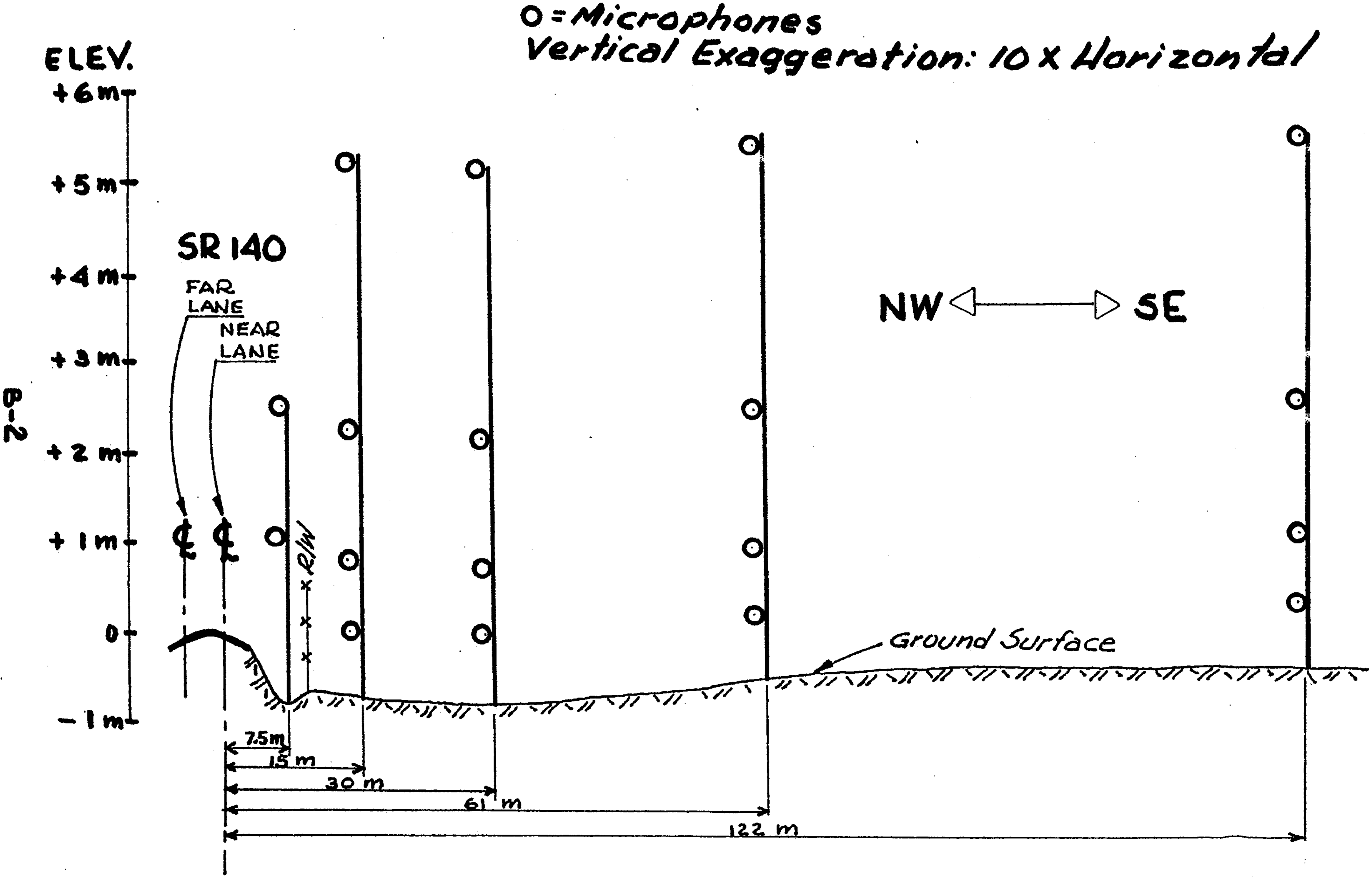


Figure B-2. Cross Section of Site G-2 "BISHOP"

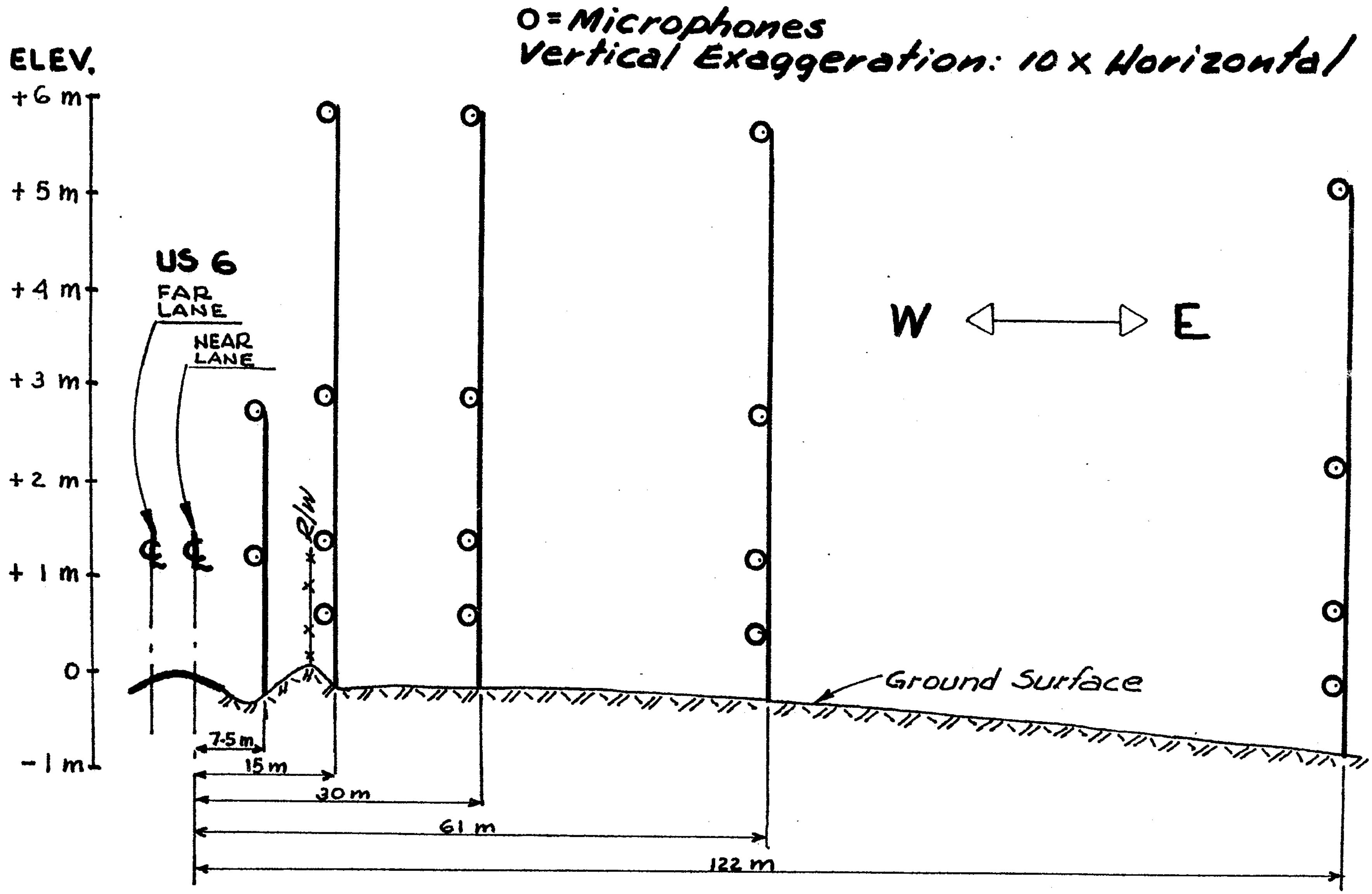


Figure B-3 Cross Section of Site G-3 "LEMOORE"

O = Microphones
Vertical Exaggeration: 10 x Horizontal

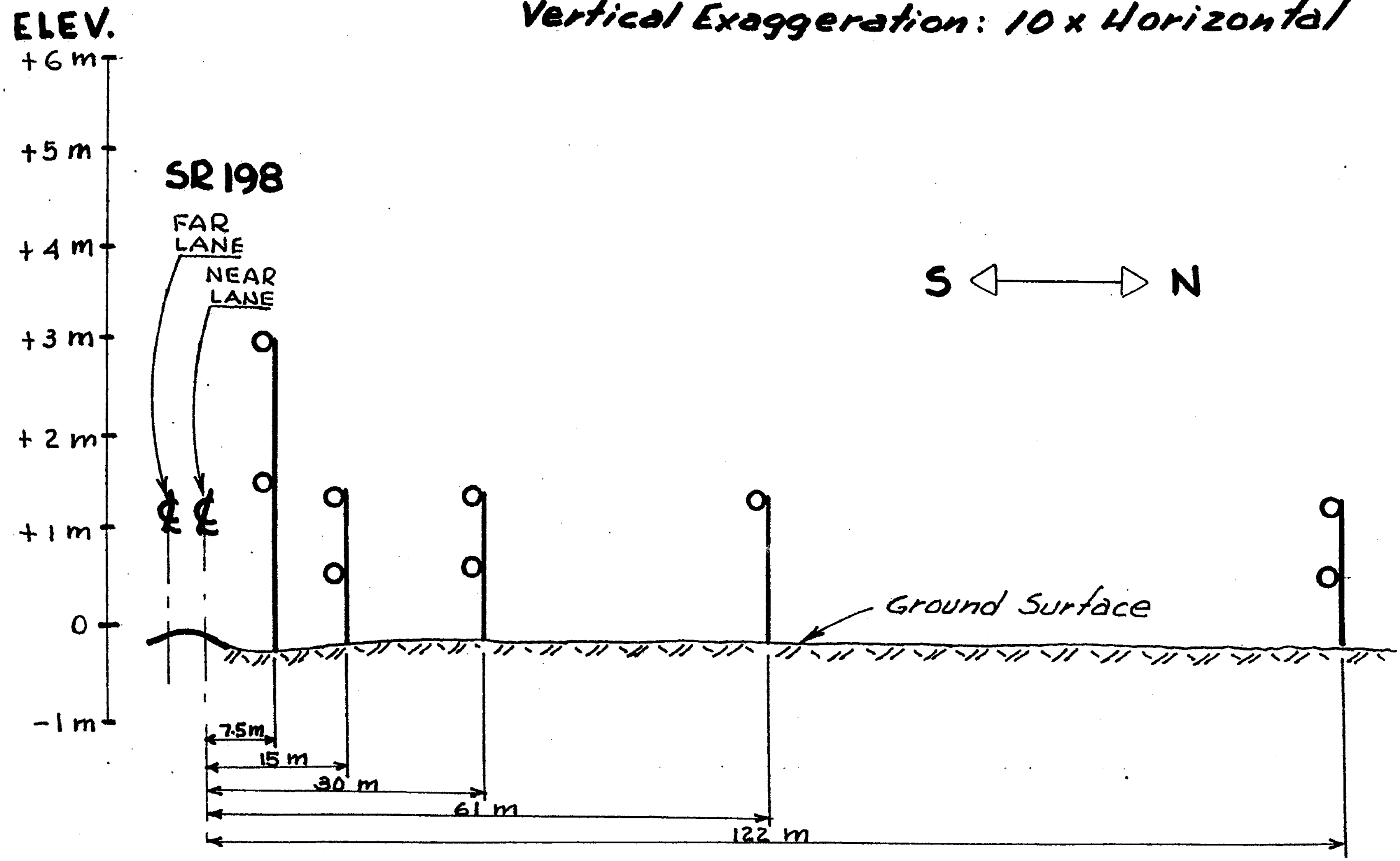


Figure B-4 Cross Section of Site G-4 "AVENUE 7"

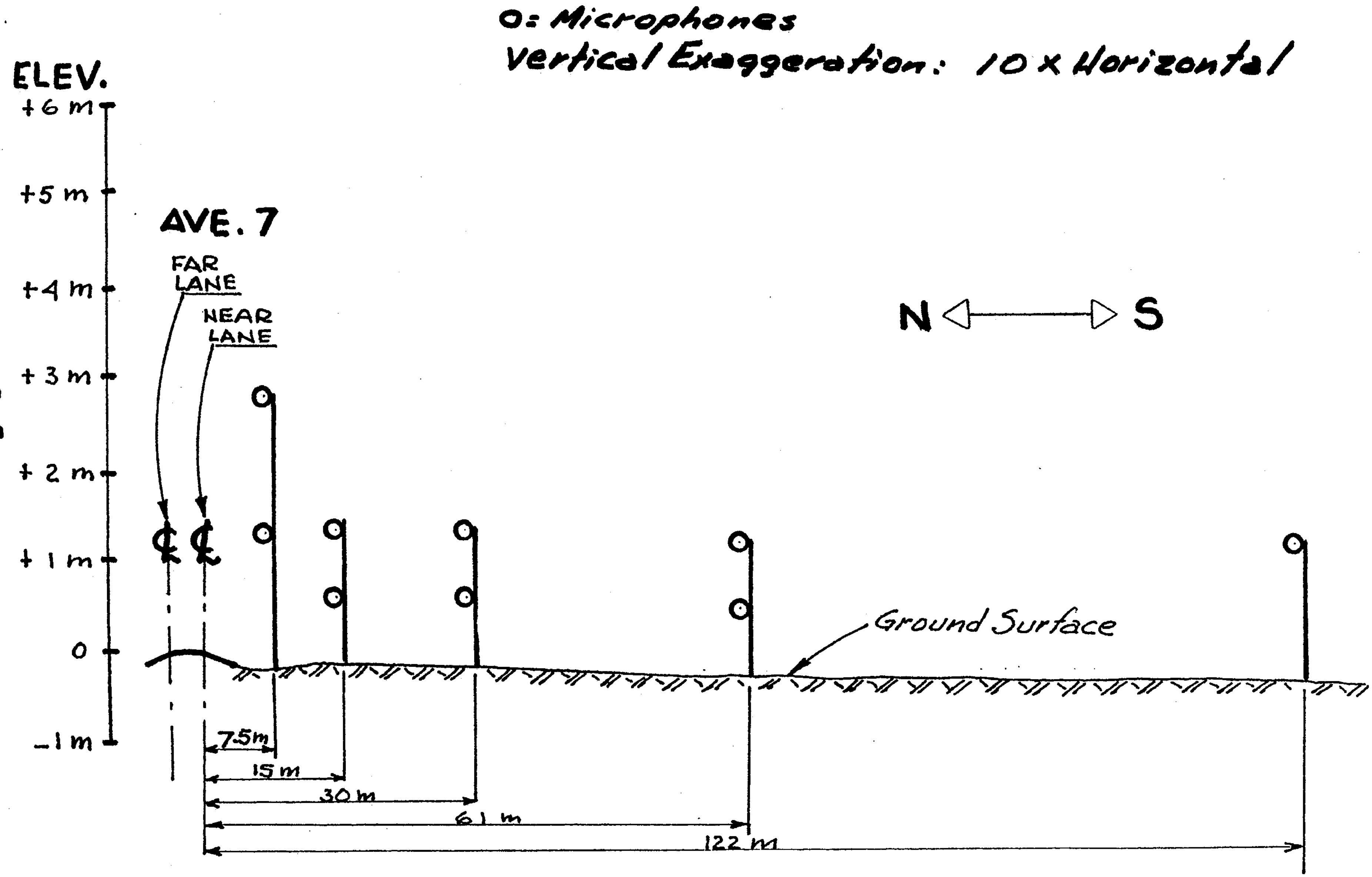


Figure B-5. Cross Sections of Sites G-7A & G-8

O=Microphones
Vertical Exaggeration: 20 x Horizontal

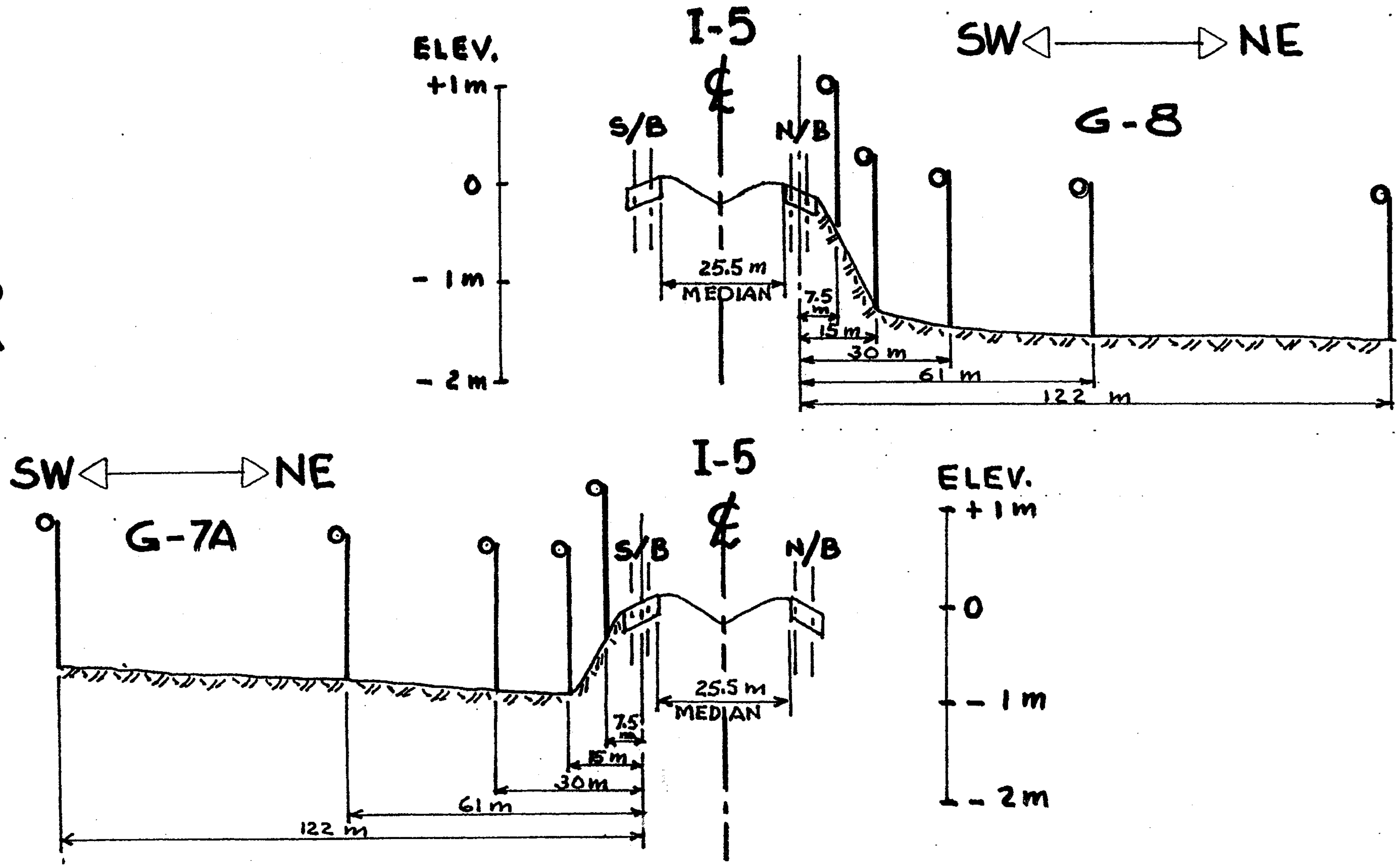


Figure B-6. Cross Section of Site PB-99

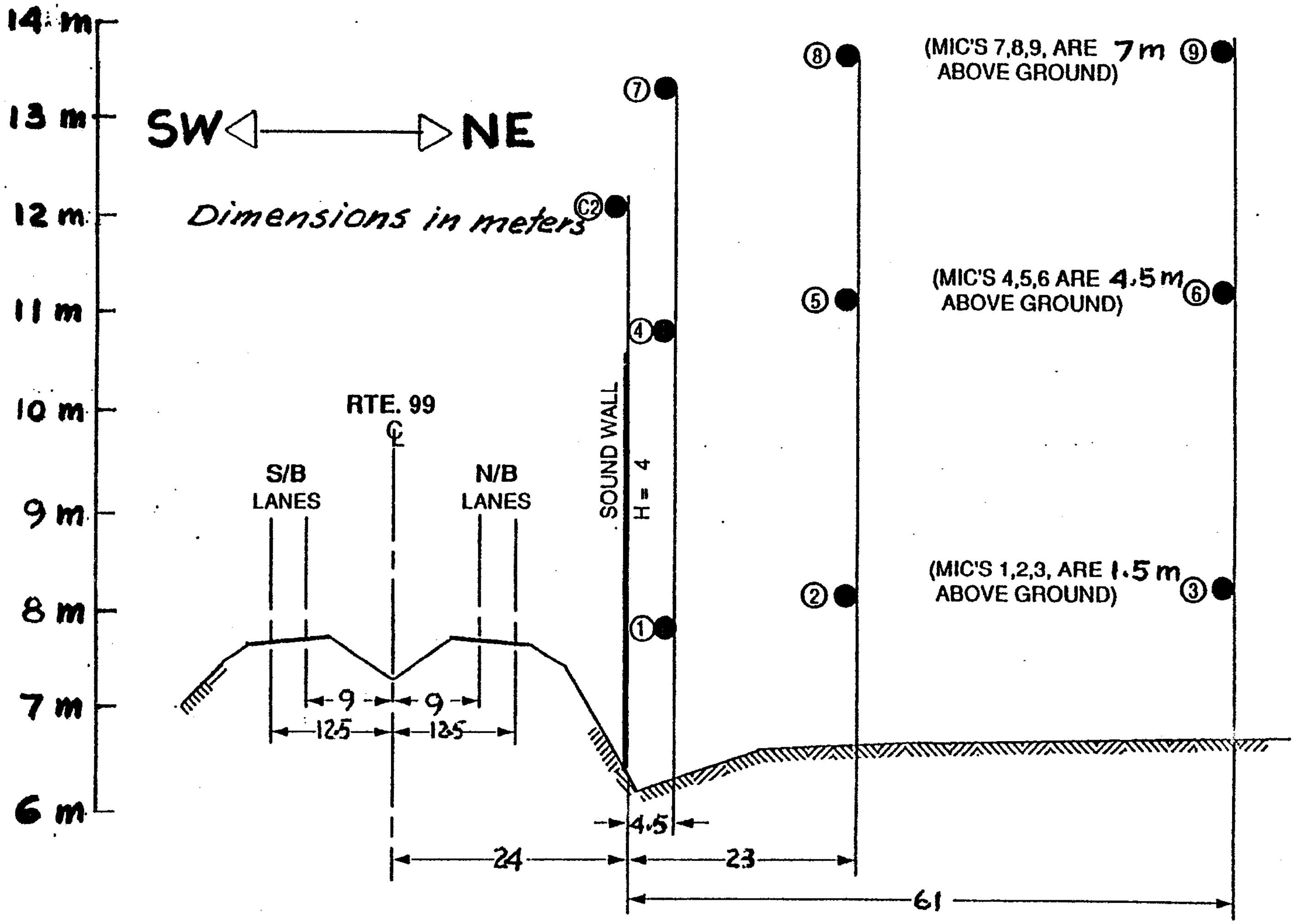


Figure B-7 Example Of Form A-1

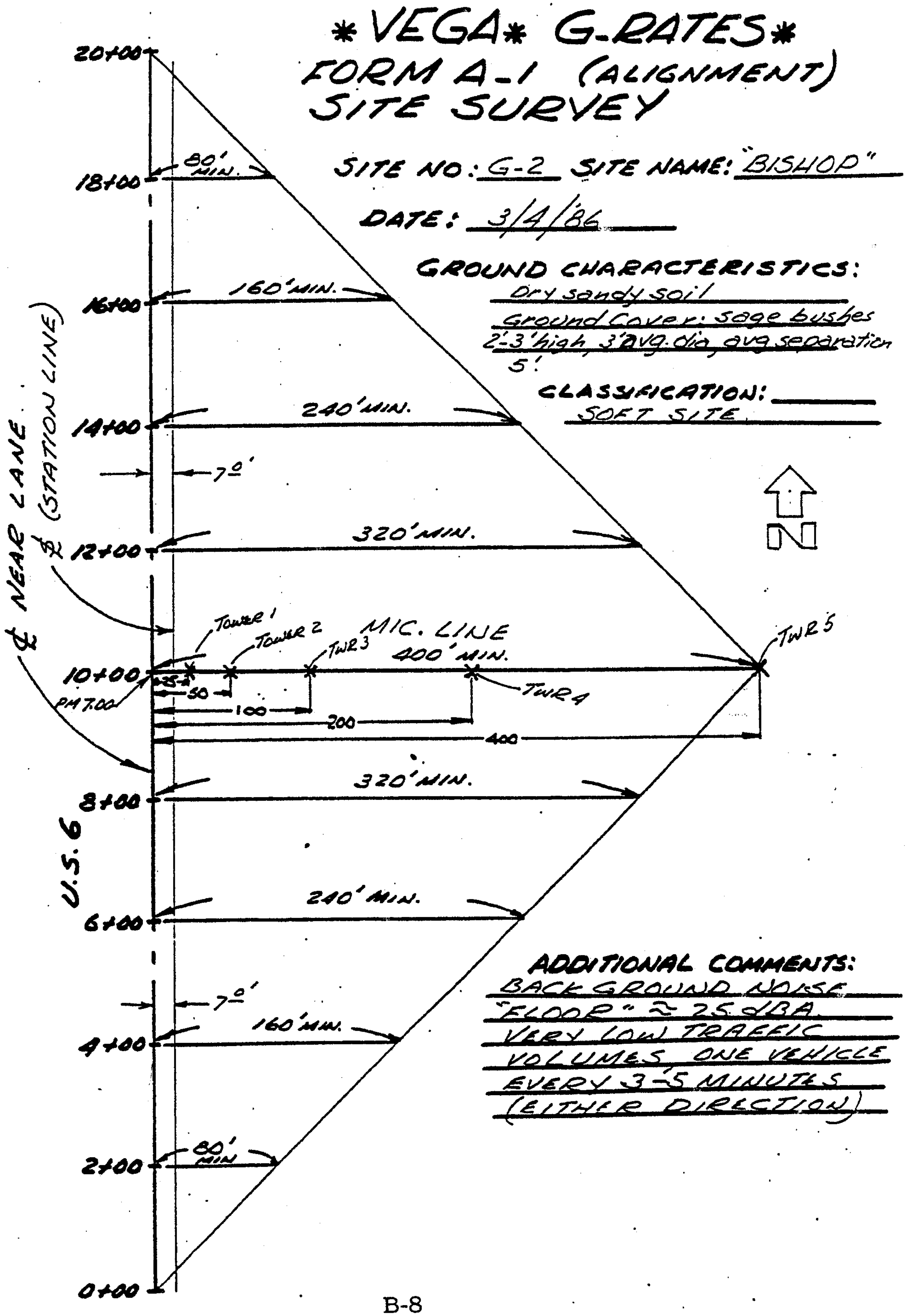


Figure B-8   Example Of Form A-2

* VEGA * G-RATES *
FORM A-2 (PROFILE ℄)
SITE SURVEY

SITE NO.: G-2 SITE NAME: "BISHOP" DATE: 3/4/86
PERSONNEL: T. Hendriks, ROD(S): Lombardi

℄	+ (Feet)	HI (Feet)	− (Feet)	ELEV. (ASSUMED)	REMARKS
0+00				$100^{\underline{0}}$ (Ft)	
	$4^{\underline{5}}$	$104^{\underline{5}}$			
2+00			$3^{\underline{5}}$	$101^{\underline{0}}$	
	$5^{\underline{8}}$	$106^{\underline{8}}$			
4+00			$3^{\underline{6}}$	$103^{\underline{2}}$	
	$4^{\underline{8}}$	$108^{\underline{0}}$			
6+00			$3^{\underline{9}}$	$104^{\underline{1}}$	
	$5^{\underline{1}}$	$109^{\underline{2}}$			
8+00			$3^{\underline{7}}$	$105^{\underline{5}}$	
	$5^{\underline{1}}$	$110^{\underline{6}}$			
10+00			$3^{\underline{7}}$	$106^{\underline{9}}$	
	$4^{\underline{5}}$	$111^{\underline{4}}$			
12+00			$4^{\underline{1}}$	$107^{\underline{3}}$	
	$4^{\underline{3}}$	$111^{\underline{6}}$			
14+00			$4^{\underline{3}}$	$107^{\underline{3}}$	
	$4^{\underline{0}}$	$111^{\underline{3}}$			
16+00			$3^{\underline{9}}$	$107^{\underline{4}}$	
	$3^{\underline{9}}$	$111^{\underline{3}}$			
18+00			$4^{\underline{3}}$	$107^{\underline{0}}$	
	$5^{\underline{0}}$	$112^{\underline{0}}$			
20+00			$3^{\underline{6}}$	$108^{\underline{4}}$	

Figure B-9 Example Of Form A-3

* VEGA * G-RATES *
FORM A-3 (CROSS SECTIONS)
SITE SURVEY

SITE NO: G-2 SITE NAME: "BISHOP DATE: 3/4/86

PERSONNEL: T. Hendriks, ROD(s) Lombardi

STA ℄	EL (Feet)	+ (Ft)	HI (Feet)	-Rod Reading (Ft) X Distance from ℄ (Ft)							
0+00	100.0	4.1	104.1	-3.9 ℄ EL:100.2	-4.1 X7.0 ℄ 100.0	-4.1 X9.0 EP 100.0	-4.6 X18.0 ℄ 99.5	-3.6 X42.0 R/W 100.5	- X	- X	- X
2+00	101.0	5.1	106.1	-4.9 ℄ EL:101.2	-5.1 X7.0 ℄ 101.0	-5.1 X9.0 EP 101.0	-5.4 X18.0 ℄ 100.7	-3.7 X42.0 R/W 102.4	-4.3 X80.0 101.8	- X	- X
4+00	103.2	4.4	107.6	-4.1 ℄ EL:103.5	-4.4 X7.0 ℄ 103.2	-4.4 X9.0 EP 103.2	-4.7 X18.0 ℄ 102.9	-3.7 X42.0 R/W 103.9	-4.6 X160.0 103.0	- X	- X
6+00	104.1	4.4	108.5	-4.0 ℄ EL:104.5	-4.4 X7.0 ℄ 104.1	-4.4 X9.0 EP 104.1	-4.4 X18.0 ℄ 104.1	-3.4 X42.0 R/W 105.1	-4.8 X240 103.7	- X	- X
8+00	105.5	4.5	110.0	-4.3 ℄ EL:105.7	-4.5 X7.0 ℄ 105.5	-4.5 X9.0 EP 105.5	-4.6 X18.0 ℄ 105.4	-3.6 X42.0 R/W 106.4	-5.2 X320 104.8	- X	- X
10+00	106.9	4.3	111.2	-4.0 ℄ EL:107.2	-4.3 X7.0 ℄ 106.9	-4.4 X9.0 EP 106.8	-4.9 X18.0 ℄ 106.3	-4.8 X25.0 TWR1 106.4	-3.6 X42.0 R/W 107.6	-4.3 X50.0 TWR2 106.9	-4.4 X100.0 TWR3 106.8
10+00 (CONT)	106.9		111.2	- ℄ EL:	-4.9 X200.0 TWR4 106.3	-6.6 X400.0 TWR5 104.6	- X	- X	- X	- X	- X
12+00	107.3	4.7	112.0	-4.3 ℄ EL:107.7	-4.7 X7.0 ℄ 107.3	-4.7 X9.0 EP 107.3	-5.5 X18.0 ℄ 106.5	-4.4 X42.0 R/W 107.6	-7.5 X320 104.5	- X	- X
14+00	107.3	4.1	111.4	-3.8 ℄ EL:107.6	-4.1 X7.0 ℄ 107.3	-4.1 X9.0 EP 107.3	-4.8 X18.0 ℄ 106.6	-4.1 X42.0 R/W 107.3	-6.0 X240 105.4	- X	- X
16+00	107.4	4.0	111.4	-3.6 ℄ EL:107.8	-4.0 X7.0 ℄ 107.4	-4.0 X9.0 EP 107.4	-4.8 X18.0 ℄ 106.6	-4.2 X42.0 R/W 107.2	-5.5 X160.0 105.9	- X	- X
18+00	107.0	4.4	111.4	-4.1 ℄ EL:107.3	-4.4 X7.0 ℄ 107.0	-4.4 X9.0 EP 107.0	-4.7 X18.0 ℄ 106.7	-4.3 X42.0 R/W 107.1	-4.1 X82 107.3	- X	- X
20+00	108.4	4.1	112.5	-3.9 ℄ EL:108.6	-4.1 X7.0 ℄ 108.4	-4.1 X9.0 EP 108.4	-5.0 X18.0 ℄ 107.5	-3.0 X42.0 R/W 109.5	- X	- X	- X
				- ℄ EL:	- X	- X	- X	- X	- X	- X	- X

Figure B-10 Example Of Form B

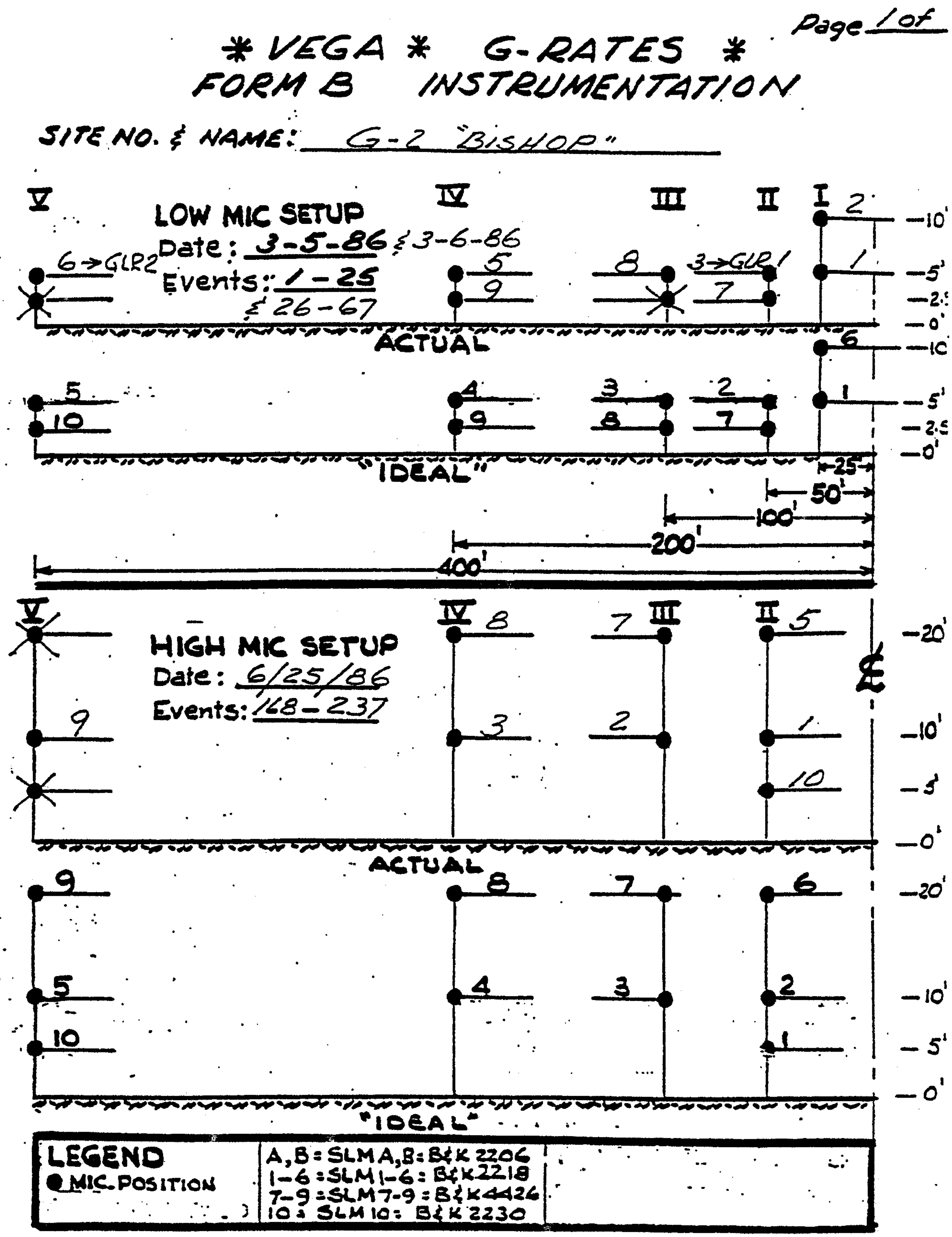


Figure B-11 Example Of Form C

VEGA G-RATES*

Page: 1

FORM C - VEHICLE OBSERVATIONS

Single events (Leq & Peak Measurements)

SITE NO: G-2 SITE NAME: "BISHOP"

DATE: 3/5/86 PERSONNEL: R. HENDRIKS, G. LOMBARDI, D. BRENT

BOTH DIRECTIONS

EVENT NO.	SPEED, MPH A	VEHICLE I.D. (1=AUTO 2=MT 3=HT)	DURATION, SEC: TO POINT OF PASS BY B	DURATION, SEC: TOTAL C	NEAR (N) OR FAR (F) LANE	SPEED, FT/SEC 1.47 x A D	DISTANCE CALC'S: DIST., FT (LT. NEAR LN / RT. FAR LN) B x D E	TOTAL DIST., FT C x D F	DIST., FT (RT. NEAR LN / LT. FAR LN) F - E	CODES * OR REMARKS (If no data taken, enter below code in appropriate col. Otherwise put BELL)
1	58	1	22	40	N					
2	51	1	19	52	N					
3	76	1	13	32	N					
4	55	1	14	30	N					
5	71	1	12	24	N					
6	64	3	4	22	N					
7	67	3	20	37	N					
8	53	1	7	18	N					
9	62	1	15	29	N					
10	58	1	11	27	N					
11	42	1	11	22	N					
12	61	3	25	48	N					
13	57	1	17	30	N					
14	52	3	25	45	N					
15	61	1	11	23	N					
16	62	1	10	28	N					
17	62	1	8	21	N					
18	58	1	13	30	N					
19	58	1	11	27	N					
20	63	3	21	38	N					
21	64	1	9	24	N					
22	58	1	12	30	N					
23	63	1	8	21	N					
24	52	3	27	55	N					
25	52	1	7	28	N					

* CODES:
C = Contaminated
S = Speed Not Constant
NG = No Good (Unspecified)
R = Radar Problem (Suspect or no speed)
T = Timing Problem (Bad or no time)
V = No Vehicle I.D., or unsure

Figure B-12 Example Of Form D

* VEGA * G-RATES * Page: 1

FORM D - ENVIRONMENTAL OBSERVATIONS

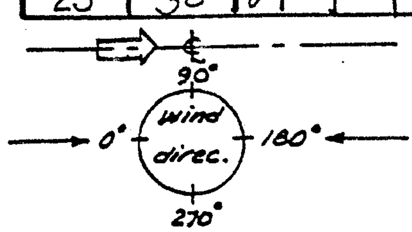
SITE NO: G-2 SITE NAME: BISHOP

DATE: 3/5/86 PERSONNEL: R. HENDRIKS

G. LOMBARDI

D. BRENT

EVENT NO.	AMBIENT NOISE, dBA	WIND SPEED 0-2 KTS	2-4 KTS	4-6 KTS	6-8 KTS	8-9 KTS	WIND DIR. (NEAREST 10°)	RELATIVE HUMIDITY, %	TEMPERATURE °F	SKY CONDITION CLEAR	PTLY CLDY	OVERCAST	HAZY	FOGGY	REMARKS
1	32		✓				360°	30%	75°	✓					
2	32		✓				360°								
3	32		✓				180°								
4	32		✓				180°								
5	32			✓			240°								
6	3-	✓					180°								
7	35	✓					180°								
8	35	✓					180°								
9	35	✓					180°		78°						
10	3-	✓					180°								
11	30	✓					180°								
12	25	✓					180°								
13	30	✓					180°								
14	30	✓					180°								
15	25	✓					180°		81°						
16	25	✓					180°								
17	25	✓					180°								
18	29	✓					180°								
19	30	✓					180°								
20	37	✓					180°		84°						
21	30	✓					180°								
22	30	✓					180°								
23	36	✓					180°								
24	47	✓					180°								
25	30	✓					180°	30%	82°						



MAXIMUM ALLOWABLE WIND SPEED

	4 KTS	6 KTS	8 KTS	9 KTS	>9 KTS
RANGE OF WIND DIRECTIONS	ALL	0-60° 120-240° 300-360°	0-40° 140-220° 320-360°	0-30° 150-210° 330-360°	NONE

Figure B-13 Example Of Noise Level Input File: Passby Leq

Record#	IDNO	MIC_1	MIC_2	MIC_3	MIC_4	MIC_5	MIC_6	MIC_7	MIC_8	MIC_9	MIC_10
1	G2-1	65.1	64.8	60.2	0.0	39.7	0.0	59.2	52.2	37.7	0.0
2	G2-2	62.1	62.9	58.8	0.0	40.5	0.0	58.0	51.0	38.2	0.0
3	G2-3	65.9	66.0	61.0	0.0	43.3	0.0	60.5	55.0	41.0	0.0
4	G2-4	60.7	60.7	55.2	0.0	38.4	0.0	54.8	48.2	36.2	0.0
5	G2-5	69.6	68.8	64.1	0.0	42.7	35.1	63.7	55.2	41.1	0.0
6	G2-6	72.2	74.2	0.0	0.0	56.5	0.0	67.7	63.2	56.1	0.0
7	G2-7	0.0	0.0	0.0	0.0	56.1	48.7	0.0	0.0	54.2	0.0
8	G2-8	66.0	65.7	60.5	0.0	45.6	0.0	59.7	52.8	45.3	0.0
9	G2-9	64.9	65.3	60.4	0.0	42.9	40.6	59.5	53.1	41.6	0.0
10	G2-10	66.4	67.4	62.8	0.0	47.2	41.7	61.8	55.1	45.3	0.0
11	G2-11	62.1	62.2	56.9	0.0	39.8	34.7	56.4	49.7	37.9	0.0
12	G2-12	65.8	66.2	62.8	0.0	50.6	45.8	62.3	56.8	49.6	0.0
13	G2-13	65.2	64.9	60.5	0.0	42.6	35.5	59.8	52.4	40.6	0.0
14	G2-14	69.0	69.1	65.5	0.0	51.3	45.3	64.6	58.4	50.1	0.0
15	G2-15	66.8	66.7	62.1	0.0	43.6	37.4	60.9	53.9	42.9	0.0
16	G2-16	63.5	65.0	61.8	0.0	41.9	35.0	59.9	52.9	39.6	0.0
17	G2-17	66.3	66.7	61.5	0.0	44.5	37.1	61.2	54.7	42.3	0.0
18	G2-18	67.5	67.9	63.4	0.0	43.7	39.1	62.0	55.0	42.2	0.0
19	G2-19	68.7	68.4	63.8	0.0	48.6	43.7	62.7	57.2	48.1	0.0
20	G2-20	74.2	73.3	0.0	0.0	54.2	48.0	68.8	63.0	52.8	0.0
21	G2-21	64.6	65.7	60.5	0.0	44.1	37.4	59.6	54.0	41.7	0.0
22	G2-22	65.8	65.9	61.1	0.0	44.5	37.7	60.2	54.2	42.8	0.0
23	G2-23	65.5	66.6	62.1	0.0	44.5	37.6	61.2	54.4	42.0	0.0
24	G2-24	72.0	72.2	69.8	0.0	58.4	54.9	69.4	0.0	57.5	0.0
25	G2-25	66.6	66.2	63.5	0.0	49.0	43.5	63.2	57.9	48.6	0.0
26	G2-26	0.0	0.0	71.1	0.0	58.9	49.8	0.0	65.4	57.1	0.0
27	G2-27	64.3	64.4	60.2	0.0	41.5	35.2	0.0	53.7	39.8	0.0
28	G2-28	62.1	62.3	58.4	0.0	40.4	32.4	0.0	51.2	38.7	0.0
29	G2-29	65.3	65.7	60.2	0.0	43.1	37.3	0.0	53.0	40.8	0.0
30	G2-30	62.4	62.8	59.4	0.0	42.1	36.3	0.0	52.2	40.7	0.0
31	G2-31	66.4	67.5	62.3	0.0	44.9	39.5	0.0	55.2	43.0	0.0
32	G2-32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	G2-33	65.5	65.7	59.2	0.0	42.2	34.7	0.0	52.5	40.5	0.0
34	G2-34	67.0	66.6	61.6	0.0	44.1	38.2	0.0	55.2	42.8	0.0
35	G2-35	69.8	69.1	65.0	0.0	47.0	38.7	0.0	57.4	45.3	0.0
36	G2-36	63.5	64.6	61.2	0.0	44.1	38.1	0.0	55.0	41.7	0.0
37	G2-37	74.3	74.5	0.0	0.0	56.1	50.1	0.0	0.0	56.2	0.0
38	G2-38	66.2	65.7	60.7	0.0	42.5	34.5	0.0	53.5	40.0	0.0
39	G2-39	66.8	66.4	62.0	0.0	43.4	38.0	0.0	54.3	42.3	0.0
40	G2-40	73.7	74.1	0.0	0.0	55.3	50.7	0.0	0.0	54.4	0.0
41	G2-41	59.6	59.6	55.7	0.0	37.8	32.0	0.0	48.3	36.8	0.0
42	G2-42	63.4	63.7	58.6	0.0	40.9	34.8	0.0	52.1	39.3	0.0
43	G2-43	69.7	68.9	66.0	0.0	50.2	43.4	0.0	59.7	49.6	0.0
44	G2-44	60.9	61.1	57.6	0.0	38.8	33.2	0.0	50.1	36.9	0.0
45	G2-45	0.0	0.0	0.0	0.0	54.8	48.0	0.0	0.0	53.7	0.0
46	G2-46	62.9	62.8	59.1	0.0	41.1	34.1	57.9	51.8	39.6	0.0
47	G2-47	66.0	66.4	61.0	0.0	42.2	34.7	59.0	52.6	40.6	0.0
48	G2-48	66.2	66.7	62.0	0.0	45.3	38.7	60.6	54.5	44.8	0.0
49	G2-49	62.5	63.5	58.8	0.0	39.9	32.2	58.3	51.5	38.5	0.0
50	G2-50	72.3	71.3	68.1	0.0	49.9	42.1	65.7	59.2	48.6	0.0
51	G2-51	69.6	68.7	66.4	0.0	53.4	49.8	65.0	60.1	53.1	0.0
52	G2-52	65.7	65.9	62.4	0.0	48.8	44.3	61.2	55.5	48.5	0.0
53	G2-53	65.3	65.5	60.3	0.0	45.2	38.4	59.4	54.3	43.0	0.0
54	G2-54	67.3	67.5	61.4	0.0	42.2	35.1	60.5	54.6	40.8	0.0
55	G2-55	62.2	62.6	57.5	0.0	39.5	33.7	55.6	50.2	38.7	0.0
56	G2-56	66.8	67.4	63.1	0.0	47.8	43.0	62.1	56.5	47.6	0.0
57	G2-57	65.8	65.8	60.9	0.0	39.4	32.2	58.9	52.6	37.8	0.0
58	G2-58	67.4	68.2	64.1	0.0	42.2	36.1	61.9	55.7	41.2	0.0
59	G2-59	68.1	68.7	63.7	0.0	41.7	34.5	61.7	55.4	40.0	0.0
60	G2-60	63.3	64.2	58.9	0.0	40.0	33.2	57.4	51.8	38.2	0.0
61	G2-61	63.3	63.4	58.9	0.0	39.7	33.9	57.6	51.5	38.2	0.0
62	G2-62	64.7	65.3	59.1	0.0	39.5	34.1	57.5	50.8	39.4	0.0

Figure B-14 Example Of Noise Level Input File: Passby L_{max}

Record#	ID_NO	MIC_1	MIC_2	MIC_3	MIC_4	MIC_5	MIC_6	MIC_7	MIC_8	MIC_9	MIC_10
1	G2-1	80.0	76.7	73.6	0.0	50.6	0.0	73.7	64.9	48.2	0.0
2	G2-2	79.8	76.5	73.5	0.0	51.7	0.0	73.2	64.2	49.3	0.0
3	G2-3	81.8	78.0	74.2	0.0	55.1	0.0	75.2	69.9	51.7	0.0
4	G2-4	74.7	71.7	67.4	0.0	47.0	0.0	68.2	60.1	43.8	0.0
5	G2-5	83.9	80.1	77.5	0.0	53.3	40.8	76.8	67.9	51.0	0.0
6	G2-6	85.8	82.0	80.5	0.0	63.2	54.8	80.0	72.0	62.4	0.0
7	G2-7	88.7	86.2	83.7	0.0	67.0	54.9	82.9	75.7	64.9	0.0
8	G2-8	77.9	74.9	71.4	0.0	51.2	0.0	71.2	61.4	51.5	0.0
9	G2-9	79.5	76.3	73.3	0.0	49.8	43.6	73.1	64.5	47.7	0.0
10	G2-10	80.6	77.5	75.2	0.0	54.1	48.4	74.8	65.7	51.9	0.0
11	G2-11	73.1	70.7	66.5	0.0	45.8	37.2	66.6	58.0	44.1	0.0
12	G2-12	81.4	78.7	76.5	0.0	58.6	50.9	76.6	68.4	57.9	0.0
13	G2-13	78.6	75.7	73.2	0.0	51.4	41.3	73.1	64.2	49.8	0.0
14	G2-14	83.6	81.4	78.3	0.0	61.2	51.5	77.8	70.5	59.9	0.0
15	G2-15	79.5	77.0	74.2	0.0	51.5	41.9	73.1	64.0	50.1	0.0
16	G2-16	79.8	76.3	74.9	0.0	52.1	39.8	74.8	65.2	49.3	0.0
17	G2-17	80.0	76.6	73.0	0.0	53.5	43.3	73.3	65.5	50.2	0.0
18	G2-18	82.1	79.3	76.4	0.0	53.7	45.2	76.1	67.0	51.2	0.0
19	G2-19	82.2	78.3	76.5	0.0	57.5	50.4	76.4	68.3	57.1	0.0
20	G2-20	85.8	82.3	80.7	0.0	63.7	56.4	80.3	73.7	62.3	0.0
21	G2-21	79.2	76.2	72.7	0.0	52.5	43.4	72.9	64.4	50.2	0.0
22	G2-22	80.1	76.8	73.4	0.0	52.1	43.2	73.3	64.9	51.0	0.0
23	G2-23	79.7	76.4	74.5	0.0	51.8	32.6	73.3	65.4	49.4	0.0
24	G2-24	88.0	85.1	81.9	0.0	67.8	59.7	81.4	74.7	66.8	0.0
25	G2-25	81.2	78.1	76.6	0.0	57.2	48.8	76.5	68.4	56.4	0.0
26	G2-26	90.0	90.5	85.3	0.0	68.7	58.3	0.0	77.7	68.0	0.0
27	G2-27	79.2	78.8	73.0	0.0	51.4	41.0	0.0	64.2	48.8	0.0
28	G2-28	77.5	77.1	71.1	0.0	49.4	39.0	0.0	63.3	47.4	0.0
29	G2-29	79.7	79.4	72.6	0.0	52.4	43.1	0.0	64.8	49.9	0.0
30	G2-30	81.2	80.6	75.0	0.0	54.2	44.2	0.0	67.1	52.7	0.0
31	G2-31	83.8	84.0	76.4	0.0	55.9	45.3	0.0	68.0	53.2	0.0
32	G2-32	81.2	81.4	75.1	0.0	54.1	45.1	0.0	66.0	52.8	0.0
33	G2-33	80.0	80.3	72.7	0.0	52.3	41.2	0.0	64.5	50.6	0.0
34	G2-34	80.1	79.9	73.5	0.0	51.8	42.3	0.0	64.9	50.6	0.0
35	G2-35	85.9	85.1	80.2	0.0	58.9	47.5	0.0	71.0	57.1	0.0
36	G2-36	80.9	80.5	75.0	0.0	54.2	44.0	0.0	67.0	52.1	0.0
37	G2-37	84.5	84.7	79.3	0.0	64.6	59.4	0.0	72.2	64.3	0.0
38	G2-38	81.8	81.7	75.3	0.0	52.6	41.1	0.0	65.9	49.9	0.0
39	G2-39	82.6	82.0	76.0	0.0	54.2	43.8	0.0	68.2	52.5	0.0
40	G2-40	87.9	87.3	82.9	0.0	65.4	57.9	0.0	75.6	64.5	0.0
41	G2-41	73.6	73.6	67.5	0.0	45.9	37.0	0.0	59.4	44.0	0.0
42	G2-42	79.0	79.0	73.2	0.0	53.5	44.3	0.0	65.9	50.7	0.0
43	G2-43	88.6	88.1	83.2	0.0	65.2	55.0	0.0	75.9	64.7	0.0
44	G2-44	76.5	76.3	70.5	0.0	50.1	39.0	0.0	62.4	47.6	0.0
45	G2-45	90.4	89.9	84.6	0.0	67.2	57.9	0.0	77.3	66.2	0.0
46	G2-46	78.5	77.6	72.1	0.0	52.0	41.4	71.7	64.0	49.9	0.0
47	G2-47	79.0	78.6	72.4	0.0	50.0	39.9	71.6	63.4	48.4	0.0
48	G2-48	83.3	82.9	77.0	0.0	56.7	47.4	76.7	68.3	56.3	0.0
49	G2-49	77.1	76.8	70.4	0.0	48.5	37.4	70.9	62.0	46.6	0.0
50	G2-50	87.2	86.8	81.0	0.0	59.5	49.6	80.6	73.0	58.3	0.0
51	G2-51	84.5	83.9	79.5	0.0	62.7	56.0	79.0	72.2	62.7	0.0
52	G2-52	82.0	81.3	75.2	0.0	58.8	51.8	75.2	68.1	58.8	0.0
53	G2-53	80.3	80.0	73.5	0.0	53.9	42.7	73.5	65.5	50.9	0.0
54	G2-54	81.5	80.9	74.3	0.0	52.7	42.1	74.5	67.0	50.6	0.0
55	G2-55	79.4	79.4	72.7	0.0	52.0	42.7	72.5	64.9	50.6	0.0
56	G2-56	83.1	82.7	76.8	0.0	58.0	49.9	76.5	68.8	57.5	0.0
57	G2-57	78.7	78.6	71.3	0.0	48.6	35.9	71.1	62.8	45.3	0.0
58	G2-58	82.0	81.9	75.9	0.0	51.4	41.0	75.2	67.2	49.2	0.0
59	G2-59	83.8	83.3	76.6	0.0	51.3	39.5	75.6	67.0	48.9	0.0
60	G2-60	81.2	81.0	73.6	0.0	52.2	40.4	73.9	65.8	49.2	0.0
61	G2-61	79.9	79.1	73.1	0.0	52.3	39.5	73.2	64.9	49.3	0.0
62	G2-62	78.9	78.6	70.7	0.0	48.7	38.2	70.4	61.6	46.7	0.0

Figure B-15 Example Of Mic Position Input File

Records	ID_NO	M1_D1_H1	M2_D2_H2	M3_D3_H3	M4_D4_H4	M5_D5_H5	M6_D6_H6	M7_D7_H7	M8_D8_H8	M9_D9_H9	M10_D10H10	NEAR_LANE
1	G2-1	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
2	G2-2	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
3	G2-3	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
4	G2-4	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
5	G2-5	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
6	G2-6	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
7	G2-7	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
8	G2-8	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
9	G2-9	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
10	G2-10	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
11	G2-11	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
12	G2-12	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
13	G2-13	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
14	G2-14	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
15	G2-15	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
16	G2-16	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
17	G2-17	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
18	G2-18	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
19	G2-19	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
20	G2-20	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
21	G2-21	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
22	G2-22	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
23	G2-23	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
24	G2-24	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
25	G2-25	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
26	G2-26	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
27	G2-27	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
28	G2-28	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
29	G2-29	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
30	G2-30	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
31	G2-31	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
32	G2-32	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
33	G2-33	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
34	G2-34	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
35	G2-35	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
36	G2-36	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
37	G2-37	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
38	G2-38	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
39	G2-39	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
40	G2-40	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
41	G2-41	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
42	G2-42	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
43	G2-43	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
44	G2-44	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
45	G2-45	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
46	G2-46	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
47	G2-47	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
48	G2-48	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
49	G2-49	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
50	G2-50	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
51	G2-51	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
52	G2-52	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
53	G2-53	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
54	G2-54	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
55	G2-55	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
56	G2-56	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
57	G2-57	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
58	G2-58	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
59	G2-59	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
60	G2-60	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
61	G2-61	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
62	G2-62	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
63	G2-63	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
64	G2-64	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
65	G2-65	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
66	G2-66	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
67	G2-67	25-5	25-10	50-5	0	200-5	400-5	50-2.5	100-5	200-2.5	0	.T.
68	G2-68	25-5	25-10	50-5	100-5	200-5	0	50-2.5	100-2.5	200-2.5	400-5	.F.
69	G2-69	25-5	25-10	50-5	100-5	200-5	0	50-2.5	100-2.5	200-2.5	400-5	.F.
70	G2-70	25-5	25-10	50-5	100-5	200-5	0	50-2.5	100-2.5	200-2.5	400-5	.F.
71	G2-71	25-5	25-10	50-5	100-5	200-5	0	50-2.5	100-2.5	200-2.5	400-5	.F.
72	G2-72	25-5	25-10	50-5	100-5	200-5	0	50-2.5	100-2.5	200-2.5	400-5	.T.
73	G2-73	25-5	25-10	50-5	100-5	200-5	0	50-2.5	100-2.5	200-2.5	400-5	.T.
74	G2-74	25-5	25-10	50-5	100-5	200-5	0	50-2.5	100-2.5	200-2.5	400-5	.F.
75	G2-75	25-5	25-10	50-5	100-5	200-5	0	50-2.5	100-2.5	200-2.5	400-5	.T.

Figure B-16 Example Of Vehicle and Passby Input File

Record#	ID_NO	MPH	VEH	T1	T
1	G2-1	58	A	22	40
2	G2-2	51	A	19	52
3	G2-3	76	A	13	32
4	G2-4	55	A	14	30
5	G2-5	71	A	12	24
6	G2-6	64	HT	4	22
7	G2-7	67	HT	20	37
8	G2-8	53	A	7	18
9	G2-9	62	A	15	29
10	G2-10	58	A	11	27
11	G2-11	42	A	11	22
12	G2-12	61	HT	25	48
13	G2-13	57	A	17	30
14	G2-14	52	HT	25	45
15	G2-15	61	A	11	23
16	G2-16	62	A	10	28
17	G2-17	62	A	8	21
18	G2-18	58	A	13	30
19	G2-19	58	A	11	27
20	G2-20	63	HT	21	38
21	G2-21	64	A	9	24
22	G2-22	58	A	12	30
23	G2-23	63	A	8	21
24	G2-24	52	HT	27	55
25	G2-25	52	A	7	28
26	G2-26	60	HT	30	44
27	G2-27	52	A	15	32
28	G2-28	60	A	13	31
29	G2-29	57	A	9	31
30	G2-30	54	A	20	58
31	G2-31	72	A	12	42
32	G2-32	53	MT	16	36
33	G2-33	61	A	15	37
34	G2-34	55	A	10	26
35	G2-35	56	A	18	52
36	G2-36	62	A	11	31
37	G2-37	53	HT	23	43
38	G2-38	54	A	17	42
39	G2-39	66	A	15	42
40	G2-40	62	HT	13	40
41	G2-41	49	A	17	32
42	G2-42	64	A	15	42
43	G2-43	65	HT	30	71
44	G2-44	47	A	25	40
45	G2-45	83	HT	14	43
46	G2-46	51	A	16	36
47	G2-47	57	A	8	25
48	G2-48	53	A	20	52
49	G2-49	51	A	9	26
50	G2-50	63	MT	20	40
51	G2-51	54	HT	26	44
52	G2-52	49	A	23	39
53	G2-53	63	A	11	27
54	G2-54	75	A	11	27
55	G2-55	58	A	38	64
56	G2-56	60	A	19	38
57	G2-57	55	A	7	18
58	G2-58	68	A	8	23
59	G2-59	69	A	11	27
60	G2-60	66	A	29	45
61	G2-61	55	A	31	43
62	G2-62	54	A	13	29

Figure B-17 Example Of Environmental Input File

Record#	ID_NO	AMBNOISE	WINDSPEED	WINDDIR	RELHUM	TEMP	SKY
1	G2-1	32	3	360	D	75	CL
2	G2-2	32	3	360	D	75	CL
3	G2-3	32	3	180	D	75	CL
4	G2-4	32	3	240	D	75	CL
5	G2-5	32	5	240	D	75	CL
6	G2-6	35	1	180	D	75	CL
7	G2-7	35	1	180	D	75	CL
8	G2-8	35	1	180	D	75	CL
9	G2-9	39	1	180	D	75	CL
10	G2-10	30	2	180	D	75	CL
11	G2-11	30	1	180	D	75	CL
12	G2-12	25	1	180	D	75	CL
13	G2-13	30	1	180	D	75	CL
14	G2-14	30	1	180	D	75	CL
15	G2-15	25	1	180	D	75	CL
16	G2-16	25	1	180	D	75	CL
17	G2-17	25	1	180	D	75	CL
18	G2-18	29	1	180	D	75	CL
19	G2-19	30	1	180	D	75	CL
20	G2-20	37	1	180	D	75	CL
21	G2-21	30	1	180	D	75	CL
22	G2-22	30	1	180	D	75	CL
23	G2-23	36	1	180	D	75	CL
24	G2-24	47	1	180	D	75	CL
25	G2-25	30	1	180	D	75	CL
26	G2-26	40	3	210	D	70	PC
27	G2-27	30	3	180	D	70	PC
28	G2-28	29	3	180	D	70	PD
29	G2-29	33	3	180	D	70	PC
30	G2-30	30	1	180	D	70	PC
31	G2-31	35	1	180	D	70	PC
32	G2-32	0	0	0	0	0	0
33	G2-33	27	1	180	D	70	PC
34	G2-34	33	1	180	D	70	PC
35	G2-35	28	1	180	D	70	PC
36	G2-36	28	1	180	D	70	PC
37	G2-37	38	3	180	D	73	PC
38	G2-38	32	3	150	D	74	PC
39	G2-39	26	3	180	D	74	PC
40	G2-40	37	3	180	D	74	PC
41	G2-41	29	3	180	D	76	PC
42	G2-42	25	1	60	D	80	PC
43	G2-43	28	1	90	D	79	PC
44	G2-44	31	1	90	D	79	PC
45	G2-45	30	1	90	D	79	PC
46	G2-46	28	1	360	D	80	PC
47	G2-47	30	3	360	D	81	PC
48	G2-48	28	5	30	D	81	PC
49	G2-49	26	3	360	D	80	PC
50	G2-50	30	3	360	D	80	PC
51	G2-51	38	1	360	D	80	PC
52	G2-52	38	1	360	D	80	PC
53	G2-53	32	1	360	D	80	PC
54	G2-54	27	1	90	D	80	PC
55	G2-55	25	1	360	D	80	PC
56	G2-56	33	1	240	D	80	PC
57	G2-57	27	1	300	D	80	PC
58	G2-58	29	1	330	D	84	PC
59	G2-59	27	3	270	D	82	PC
60	G2-60	27	1	360	D	83	PC
61	G2-61	33	1	360	D	83	PC
62	G2-62	30	1	360	D	83	PC

APPENDIX C

SUMMARY OF α RESULTS

TABLE C-1. SUMMARY OF α RESULTS

AUTOS

SITE No.	HEIGHT m (ft)	DISTANCE, m (ft) 7.5-15 (25-50) L_{eq}	7.5-15 (25-50) L_{max}	15-30 (50-100) L_{eq}	15-30 (50-100) L_{max}	15-61 (50-200) L_{eq}	15-61 (50-200) L_{max}	15-122 (50-400) L_{eq}	15-122 (50-400) L_{max}
G-1	0.8 (2.5)	N/D	N/D	2.1	1.6	2.0	2.0	1.7	1.6
G-1	1.5 (5)	1.0	0.5	2.0	1.2	2.1	1.7	2.0	1.8
G-1	3 (10)	N/D	N/D	0.8	0.2	1.3	0.6	1.8	1.5
G-1	6 (20)	N/D	N/D	0.1	-.2	0.5	0.0	1.3	0.7
G-2	0.8 (2.5)	N/D	N/D	1.8	1.5	2.1	1.9	N/D	1.6
G-2	1.5 (5)	0.6	0.2	1.8	1.2	2.1	1.7	1.8	1.5
G-2	3 (10)	N/D	N/D	0.9	0.3	1.8	1.1	2.0	0.2
G-2	6 (20)	N/D	N/D	0.2	-.4	0.7	0.0	N/D	N/D
G-3	0.8 (2.5)	N/D	N/D	1.7	1.5	N/D	N/D	1.8	1.4
G-3	1.5 (5)	0.6	0.0	1.6	1.2	1.8	1.4	1.8	1.5
G-3	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
G-3	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
G-4	0.8 (2.5)	N/D	N/D	1.1	0.6	1.5	1.1	N/D	1.1
G-4	1.5 (5)	1.0	0.6	0.9	0.6	1.2	0.8	1.3	0.9
G-4	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
G-4	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D

SITE No.	HEIGHT m (ft)	DISTANCE, m (ft) 30-61 (100-200) L_{eq}	30-61 (100-200) L_{max}	30-122 (100-400) L_{eq}	30-122 (100-400) L_{max}	61-122 (200-400) L_{eq}	61-122 (200-400) L_{max}
G-1	0.8 (2.5)	1.9	2.3	1.5	1.7	1.5	1.8
G-1	1.5 (5)	2.2	2.1	2.0	2.1	2.0	2.4
G-1	3 (10)	2.0	1.0	2.4	2.1	2.4	3.1
G-1	6 (20)	0.9	0.2	1.6	1.1	2.1	1.9
G-2	0.8 (2.5)	2.2	2.2	N/D	N/D	N/D	N/D
G-2	1.5 (5)	2.4	2.1	1.7	1.7	1.0	1.3
G-2	3 (10)	2.6	2.0	2.3	2.1	2.1	2.3
G-2	6 (20)	1.3	0.4	N/D	N/D	N/D	N/D
G-3	0.8 (2.5)	N/D	N/D	1.7	1.4	N/D	N/D
G-3	1.5 (5)	2.0	1.6	1.8	1.6	2.0	2.4
G-3	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D
G-3	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D
G-4	0.8 (2.5)	1.9	1.5	N/D	N/D	N/D	N/D
G-4	1.5 (5)	1.6	1.1	1.5	1.1	1.3	1.1
G-4	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D
G-4	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D

Note: N/D = No Data

TABLE C-2. SUMMARY OF α RESULTS

MEDIUM TRUCKS

SITE No.	HEIGHT m (ft)	7.5-15 (25-50) L_{eq}	7.5-15 (25-50) L_{max}	15-30 (50-100) L_{eq}	15-30 (50-100) L_{max}	15-61 (50-200) L_{eq}	15-61 (50-200) L_{max}	15-122 (50-400) L_{eq}	15-122 (50-400) L_{max}
		DISTANCE, m (ft)							
G-1	0.8 (2.5)	N/D	N/D	2.1	1.5	1.9	2.0	N/D	2.0
G-1	1.5 (5)	1.0	0.5	1.9	1.1	2.1	1.7	N/D	1.7
G-1	3 (10)	N/D	N/D	0.4	0.0	1.3	0.6	1.5	1.2
G-1	6 (20)	N/D	N/D	0.1	0.1	0.4	0.0	1.3	0.7
G-2	0.8 (2.5)	N/D	N/D	1.6	1.3	1.9	1.7	N/D	1.7
G-2	1.5 (5)	0.5	0.0	1.9	1.1	2.0	1.6	1.8	1.6
G-2	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
G-2	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
G-3	0.8 (2.5)	N/D	N/D	1.1	0.8	N/D	N/D	1.4	1.1
G-3	1.5 (5)	0.3	0.2	1.2	0.9	1.3	1.0	1.4	1.1
G-3	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
G-3	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
G-4	0.8 (2.5)	N/D	N/D	1.0	0.6	1.4	1.1	N/D	1.1
G-4	1.5 (5)	0.8	0.3	0.7	0.3	1.2	0.6	1.2	0.8
G-4	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
G-4	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D

SITE No.	HEIGHT m (ft)	30-61 (100-200) L_{eq}	30-61 (100-200) L_{max}	30-122 (100-400) L_{eq}	30-122 (100-400) L_{max}	61-122 (200-400) L_{eq}	61-122 (200-400) L_{max}
		DISTANCE, m (ft)					
G-1	0.8 (2.5)	1.8	2.5	N/D	N/D	N/D	N/D
G-1	1.5 (5)	2.2	2.3	N/D	N/D	N/D	N/D
G-1	3 (10)	2.1	1.3	2.1	1.6	2.1	2.3
G-1	6 (20)	0.2	-.4	1.4	0.6	3.2	2.4
G-2	0.8 (2.5)	2.2	2.0	N/D	N/D	N/D	N/D
G-2	1.5 (5)	2.1	2.1	1.8	1.7	1.4	1.3
G-2	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D
G-2	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D
G-3	0.8 (2.5)	N/D	N/D	1.5	1.2	N/D	N/D
G-3	1.5 (5)	1.4	1.1	1.5	1.2	N/D	N/D
G-3	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D
G-3	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D
G-4	0.8 (2.5)	1.8	1.5	N/D	N/D	N/D	N/D
G-4	1.5 (5)	1.3	0.7	1.2	0.8	1.4	1.3
G-4	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D
G-4	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D

Note: N/D = No Data

TABLE C-3. SUMMARY OF α RESULTS

HEAVY TRUCKS

SITE No.	HEIGHT m (ft)	7.5-15 (25-50) L_{eq}	7.5-15 (25-50) L_{max}	15-30 (50-100) L_{eq}	15-30 (50-100) L_{max}	15-61 (50-200) L_{eq}	15-61 (50-200) L_{max}	15-122 (50-400) L_{eq}	15-122 (50-400) L_{max}
				DISTANCE, m (ft)					
G-1	0.8 (2.5)	N/D	N/D	1.9	1.1	2.0	1.5	1.9	1.7
G-1	1.5 (5)	1.0	0.4	1.5	1.0	1.9	1.1	2.1	1.2
G-1	3 (10)	N/D	N/D	0.3	0.0	0.6	0.1	1.2	1.6
G-1	6 (20)	N/D	N/D	0.1	-.1	0.3	0.0	0.8	0.3
G-2	0.8 (2.5)	N/D	N/D	1.0	0.4	1.5	0.9	N/D	1.0
G-2	1.5 (5)	0.2	0.0	1.3	0.8	1.4	1.0	1.6	1.0
G-2	3 (10)	N/D	N/D	0.5	0.1	1.4	0.7	1.6	0.2
G-2	6 (20)	N/D	N/D	0.3	-.1	0.5	0.1	N/D	0.1
G-3	0.8 (2.5)	N/D	N/D	0.9	0.5	N/D	N/D	1.4	1.1
G-3	1.5 (5)	0.6	0.2	1.0	0.6	1.0	0.7	1.4	1.0
G-3	3 (10)	N/D	N/D	N/D	N/D	N/D	0.0	N/D	0.2
G-3	6 (20)	N/D	N/D	N/D	N/D	N/D	0.0	N/D	0.1
G-4	0.8 (2.5)	N/D	N/D	0.9	0.4	1.5	1.1	N/D	1.2
G-4	1.5 (5)	0.6	0.1	0.4	0.1	0.9	0.4	1.4	0.9
G-4	3 (10)	N/D	N/D	N/D	N/D	N/D	0.0	N/D	0.2
G-4	6 (20)	N/D	N/D	N/D	N/D	N/D	0.0	N/D	0.1

SITE No.	HEIGHT m (ft)	30-61 (100-200) L_{eq}	30-61 (100-200) L_{max}	30-122 (100-400) L_{eq}	30-122 (100-400) L_{max}	61-122 (200-400) L_{eq}	61-122 (200-400) L_{max}
				DISTANCE, m (ft)			
G-1	0.8 (2.5)	2.2	1.9	1.8	1.9	1.4	1.9
G-1	1.5 (5)	2.3	2.4	2.3	2.4	2.3	3.1
G-1	3 (10)	0.8	0.2	1.5	0.8	2.3	1.5
G-1	6 (20)	0.4	0.0	1.1	1.6	1.8	1.3
G-2	0.8 (2.5)	1.9	1.6	N/D	N/D	N/D	N/D
G-2	1.5 (5)	1.2	0.7	1.6	1.2	2.3	1.6
G-2	3 (10)	2.1	1.2	2.0	1.5	1.9	1.7
G-2	6 (20)	0.9	0.3	N/D	N/D	N/D	N/D
G-3	0.8 (2.5)	N/D	N/D	1.6	1.3	N/D	N/D
G-3	1.5 (5)	1.2	0.7	1.6	1.2	2.3	1.6
G-3	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D
G-3	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D
G-4	0.8 (2.5)	1.6	1.2	N/D	N/D	N/D	N/D
G-4	1.5 (5)	1.3	0.8	1.8	1.4	1.2	1.9
G-4	3 (10)	N/D	N/D	N/D	N/D	N/D	N/D
G-4	6 (20)	N/D	N/D	N/D	N/D	N/D	N/D

Note: N/D = No Data

APPENDIX D

α SENSITIVITY STUDY

α SENSITIVITY STUDY

Hyperbolic α vs $\alpha = 0.5$

Noise Predictions Using FHWA-RD-77-108 (FHWA ModeL)

With California Vehicle Noise (Calveno) Emission Levels

BASE PARAMETERS:

* Single Line Source
* Infinite Roadway
* Traffic Volume: 2000 Vehicles Per Hour
* Traffic Speed: 88 km/hr (55 mph)
* Unless Otherwise Indicated, Traffic Mix:
  - Heavy Trucks 7%
  - Medium Trucks 0%
  - Autos 93%

KEY:

D = Distance from Source to Receiver

Hyp.α = Hyperbolic α

Reference Height = Receiver Height of 1.5 m (5 Ft)

NOTE:

This sensitivity study was originally run with a special version of LEQV2 computer program in English units

A. SENSITIVITY TO TRAFFIC MIX; AT REFERENCE HEIGHT

1. D = 30 m (100 ft)

TRAFFIC MIX	L_{eq}(h), dBA USING: 1. HYP.α	2. $\alpha = 0.5$	DIFF.(1-2)
a. 2% HT,98% A	66.4	68.2	-1.8
b. 5% HT,95% A	67.7	69.3	-1.6
c. 7% HT,93% A* (Reference)	68.5	69.9	-1.4
d.10% HT,90% A	69.3	70.6	-1.3
e.15% HT,85% A	70.5	71.7	-1.2
f. 20% HT,80% A	71.4	72.5	-1.1

A. SENSITIVITY TO TRAFFIC MIX; AT REF. HEIGHT (Continued)

2. D = 61 m (200 ft)

TRAFFIC MIX	L_{eq}(h), dBA USING: 1. HYP. α	2. α = 0.5	DIFF.(1-2)
a. 2% HT,98% A	58.6	63.6	-5.0
b. 5% HT,95% A	60.2	64.7	-4.5
c. 7% HT,93% A* (Reference)	61.0	65.3	-4.3
d. 10% HT,90% A	62.0	66.1	-4.1
e. 15% HT,85% A	63.3	67.2	-3.9
f. 20% HT,80% A	64.3	68.0	-3.7

3. D = 122 m (400 ft)

TRAFFIC MIX	L_{eq}(h), dBA USING: 1. HYP. α	2. α = 0.5	DIFF.(1-2)
a. 2% HT,98% A	50.6	59.1	-8.5
b. 5% HT,95% A	52.5	60.2	-7.7
c. 7% HT,93% A* (Reference)	53.4	60.8	-7.4
d. 10% HT,90% A	54.6	61.6	-7.0
e. 15% HT,85% A	55.9	62.6	-6.7
f. 20% HT,80% A	57.0	63.5	-6.5

B. SENSITIVITY TO DISTANCE; REF. TRAFFIC MIX; REF. HEIGHT

DISTANCE, m (Ft)		L_{eq}(h), dBA USING: 1. HYP. α	2. α = 0.5	DIFF.(1-2)
1.	15 (50)	75.0	74.4	+0.6
2.	30 (100)	68.5	69.9	-1.4
3.	46 (150)	64.1	67.2	-3.1
4.	61 (200)	61.0	65.3	-4.3
5.	76 (250)	58.5	63.9	-5.4
6.	91 (300)	56.5	62.7	-6.2
7.	107 (350)	54.8	61.7	-6.9
8.	122 (400)	53.4	60.8	-7.4

C. SENSITIVITY TO HEIGHT; REF. TRAFFIC MIX

1. D = 30 m (100 ft)

REC.HEIGHT, m (Ft)		L_{eq}(h), dBA USING: 1. HYP. α	2. $\alpha = 0.5$ $\alpha = 0.0$*	DIFF.(1-2)
a.	0.8 (2.5)	67.6	69.9	-2.3
b.	1.5 (5) (Ref.)	68.5	69.9	-1.4
c.	2.1 (7)	69.2	69.9	-0.7
d.	2.7 (9)	69.8	69.9	-0.1
e.	3.4 (11)	70.6	69.9	+0.7
f.	4.0 (13)	71.4	69.9	+1.5
g.	4.6 (15)	71.9	72.6*	-0.7
h.	5.2 (17)	72.2	72.6*	-0.4
i.	5.8 (19)	72.6	72.6*	0.0

2. D = 61 m (200 ft)

REC.HEIGHT, m (Ft)		L_{eq}(h), dBA USING: 1. HYP. α	2. $\alpha = 0.5$ $\alpha = 0.0$*	DIFF.(1-2)
a.	0.8 (2.5)	59.2	65.3	-6.1
b.	1.5 (5) (Ref.)	61.3	65.3	-4.3
c.	2.1 (7)	62.5	65.3	-2.8
d.	2.7 (9)	64.0	65.3	-1.3
e.	3.4 (11)	65.6	65.3	+0.3
f.	4.0 (13)	67.3	65.3	+2.0
g.	4.6 (15)	68.3	69.6*	-1.3
h.	5.2 (17)	68.8	69.6*	-0.8
i.	5.8 (19)	69.6	69.6*	0.0

3. D = 122 (400 ft)

REC.HEIGHT, m (Ft)		L_{eq}(h), dBA USING: 1. HYP. α	2. $\alpha = 0.5$ $\alpha = 0.0$*	DIFF.(1-2)
a.	0.8 (2.5)	50.6	60.8	-10.2
b.	1.5 (5) (Ref.)	53.4	60.8	-7.4
c.	2.1 (7)	55.8	60.8	-5.0
d.	2.7 (9)	58.2	60.8	-2.6
e.	3.4 (11)	60.7	60.8	-0.1
f.	4.0 (13)	63.3	60.8	+2.5
g.	4.6 (15)	64.8	66.6*	-1.8
h.	5.2 (17)	65.5	66.6*	-1.1
i.	5.8 (19)	66.6	66.6*	0.0

D. SENSITIVITY TO BARRIERS; REF. TRAFFIC; REF. HEIGHT

1. D = 30 m (100 ft)

Source to Barr. = 9 m (30 Ft); Barr. to Rec.= 21 m (70 Ft)

BARRIER HEIGHT, m (Ft)	L_{eq}(h), dBA USING: 1. HYP. α	2. α = 0.5* α = 0.0	IL 1	IL 2
a. W/O BARR.	68.5	69.9*	N/A	N/A
b. 1.8 (6)	64.3	66.4	4.2	3.5
c. 2.4 (8)	63.9	65.5	4.6	4.4
d. 3.0 (10)	62.9	64.0	5.6	5.9
e. 3.7 (12)	61.3	62.1	7.2	7.8
f. 4.3 (14)	59.8	60.6	8.7	9.3
g. 4.9 (16)	58.6	59.2	9.9	10.7
h. 5.5 (18)	57.7	58.2	10.8	11.7
i. 6.1 (20)	56.9	57.3	11.6	12.6

2. D = 61 m (200 ft)

Source to Barr. = 9 m (30 Ft); Barr. to Rec.= 52 m (170 Ft)

BARRIER HEIGHT, m (Ft)	L_{eq}(h), dBA USING: 1. HYP. α	2. α = 0.5* α = 0.0	IL 1	IL 2
a. W/O BARR.	61.3	65.3*	N/A	N/A
b. 1.8 (6)	57.2	63.5	4.1	1.8
c. 2.4 (8)	57.8	62.6	3.5	2.7
d. 3.0 (10)	58.2	61.4	3.1	3.9
e. 3.7 (12)	57.2	59.8	4.1	5.5
f. 4.3 (14)	56.1	58.3	5.2	7.0
g. 4.9 (16)	55.1	56.9	6.2	8.4
h. 5.5 (18)	54.3	55.8	7.0	9.5
i. 6.1 (20)	53.9	54.9	7.4	10.4

3. D = 122 m (400 ft)

Source to Barr. = 9 m (30 Ft); Barr. to Rec.= 113 m (370 Ft)

BARRIER HEIGHT, m (Ft)	L_{eq}(h), dBA USING: 1.HYP. α	2. α = 0.5* α = 0.0	IL 1	IL 2
a. W/O BARR.	53.4	60.8*	N/A	N/A
b. 1.8 (6)	50.2	60.5	3.2	0.3
c. 2.4 (8)	51.8	59.6	1.6	1.2
d. 3.0 (10)	53.3	58.6	0.1	2.2
e. 3.7 (12)	53.0	57.1	0.4	3.7
f. 4.3 (14)	52.1	55.6	1.3	5.2
g. 4.9 (16)	51.3	54.3	2.1	6.5
h. 5.5 (18)	50.8	53.1	2.6	7.7
i. 6.1 (20)	50.4	52.2	3.0	8.6